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Telecommunications Consumer Protections Are Vital

Editorial

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Abstract: Papers in the March 2018 issue of the *Journal* cover advances in telecommunications technologies and regulation, historical events, and book reviews. Looking more widely, the Australian Government has responded to the increase in complaints about telecommunications services by ordering yet another review. Telecommunications consumers are rightly concerned that access to reliable and modern telecommunications is a key aspect of life today. Telecommunications consumer protections are vital and there needs to be a timely response to the rapid rise in complaints that was accurately predicted four years ago by industry experts. The *Journal* would welcome contributions on this and other topics.

In This Issue

In this issue, the *Journal* includes topical articles that cover international telecommunications, the National Broadband Network, historical events and two reviews of recent books about Charles Todd, a pioneer in Australian telecommunications.

The National Broadband Network: What Difference will it make to Broadband Availability in Australia? provides a bottom-up analysis of broadband availability in Australia without the NBN and with the NBN.

Handover with Buffering for Distributed Mobility Management (DMM) in Software Defined Mobile Networks propose a DMM solution with handover operations for SDN-enabled mobile networks.

A Trust-based Defence Scheme for Mitigating Blackhole and Selective Forwarding Attacks in the RPL Routing Protocol is a follow-up research work to validate the authors' simulation study, which addressed Blackhole attacks in the RPL routing protocol. In addition, Selective Forwarding attacks are also addressed.

Vale Roger Banks: A Tribute is an obituary that outlines his life from the early days in Victoria, through his career with the PMG and Telecom, to his post-retirement contributions as a board member and supporter of engineering education.

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Introduction of Crossbar Switching Equipment to the Australian Telephone Network is a historic paper by Roger Banks from the *Journal* in 1961 summarising the investigation and selection of Crossbar Switching Equipment for the Australian Telephone Network.

'And Now the Biography': 150 Years of 'Telegraph' Todd discusses the genesis of the recent Todd biography entitled *Behind the Legend: The Many Worlds of Charles Todd*, examining the changing historical perspectives on Todd and his achievements.

Behind the Legend: A New and Comprehensive Biography of Charles Todd is a review of the recent Todd biography *Behind the Legend - The Many Worlds of Charles Todd*.

The Weatherman from Greenwich: A new book 'about' Charles Todd is a review of the recently released book titled *The Weatherman from Greenwich: Charles Todd – 1826 to 1910*.

A Historical Perspective on WRESAT, the First Satellite Launched from Australian Soil is a personal account of the project, involving the satellite's telemetry system and a temporary extension to Oodnadatta of Woomera's flight safety system. The paper goes on to describe events following the successful launch, and the celebration of the 50th anniversary in 2017. Finally, there is a discussion of the politics and technologies behind WRESAT.

Australian Broadband Regulation Reviewed establishes the relationship between the condition of Australian broadband competition and Australia's history of broadband regulation.

Telecommunications Consumer Protections Are Vital

The Australian Government response (Fifield, 2018) to the release of the Telecommunications Industry Ombudsman's (TIO) six month update is welcomed, but should have occurred four years ago when industry experts warned the government that the multi-technology mix National Broadband Network (NBN) would lead to an increase in complaints of varying types and introduce complexity for the TIO in being able to identify rectification responsibility, particularly in relation to NBN Co.

There is a need for the government to rapidly respond to the problems faced by telecommunications consumers. The number and type of telecommunications related complaints identified by the TIO is unacceptable. Government equivocation about the effects that the NBN is having on the number, types and responsibility for complaints presented to the TIO is not helping to solve the underlying problems and to put in place a regime that will permit the TIO to adequately deal with the complaints in a timely manner.

The Minister for Communications and the Arts, Senator Mitch Fifield, has announced 'a review of the telecommunications consumer protections framework for a post-2020

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environment' (Fifield, 2018). The review is necessary, but what is to happen prior to the 'post-2020 environment'?

There is an urgent need for the government to provide the TIO with additional interim powers to address the existing and future complaints (prior to the 'post-2020 environment'), identify responsibility for rectification works and to resolve matters related to the payment of compensation.

The *Journal* would welcome papers on what the telecommunications consumer protections framework for a post-2020 environment should look like.

The *Journal*, Looking Forward

Australian telecommunications is moving forward at a rapid rate, and the introduction of 5G next year will speed up the reach and utilisation of telecommunication services. The *Journal* is calling for papers on how 5G will affect Australian telecommunications consumers.

The topics of *International Telecommunications Legislation and Regulations* and *International Mobile Cellular Regulation and Competition* are set to continue for some time as the opportunity to attract papers from around the globe continues. We encourage papers that reflect on where the telecommunications market is now, how it got to where it is, and what is going to happen next.

Papers are invited for upcoming issues. With your contributions, the *Journal* will continue to provide readers with exciting and informative papers covering a range of local and international topics. The Editorial Advisory Board also values input from our readership, so please let us know what themes you would like to see in the coming year.

All papers related to telecommunications and the digital economy are welcome and will be considered for publication after the double-blind peer-review process.

Mark A Gregory

Reference

Fifield. M. 2018. 'Statement in Response to TIO Half-Yearly Complaints Report', 17 April 2018. Retrieved from http://www.minister.communications.gov.au/mitch_fifield/news/statement_in_response_to_tio_half-yearly_complaints_report .

The National Broadband Network

What Difference Will It Make to Broadband Availability in Australia?

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Abstract

We provide a bottom-up analysis of broadband availability in Australia without the NBN and with the NBN. For Australia without the NBN, we have assumed that broadband availability, in terms of access speed, would have continued to evolve; in particular, we have assumed that all DSL access would have been enhanced to ADSL2+. For Australia with the NBN, we concentrate on the Multi-Technology Mix version now being deployed in the fixed-line footprint. The NBN can make a difference both in terms of the geographical availability of broadband access and in the maximum access speeds provided. We consider both these aspects for the period after the current NBN has been fully deployed. Our analysis is based solely on publicly available information and census data from 2011. We find that the NBN will extend fixed-line broadband availability only marginally. In terms of access speed, we find that a further 17% of the population will have access to 10 Mb/s downstream and a further 65% of the population will have access to 25 Mb/s. Only a further 11% of the population will have access to 10 Mb/s and above upstream. The improvement in availability is particularly marked in outer suburban areas of the major cities and in regional centres.

Keywords: NBN, fixed broadband, spatial analysis, downstream, upstream

Introduction

The concept of a National Broadband Network (NBN) was developed by the Australian Government in the period 2007-2009, culminating in a project for a wholesale only, open-access network based primarily on fibre to the premises (FTTP) technology. Initial deployments began in 2010. Following the change in governing party in 2013, the plan was changed to a Multi-Technology Mix, with some FTTP and a wider use of Fibre to the Node

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(FTTN), Hybrid Fibre-Coax (HFC), Fixed Wireless, and Broadband Satellite. The aim is to provide the capability for at least 50 Mb/s downstream (that is, towards the end user) access to 90% of premises, with the remaining 10% of premises having access to at least 25 Mb/s downstream. In the plan announced in 2014, deployment of the NBN was to be completed by 2019.

We have undertaken a study to examine the economic and other impacts of the NBN. As part of this study, we have estimated how much difference the NBN will make to broadband availability in Australia. The NBN can affect the availability of broadband in two ways. Firstly, it can improve the geographical availability: that is, areas otherwise not served by fixed broadband would be served. Secondly, it can improve the access speeds available: that is, an area served by ADSL2+ at up to 24 Mb/s downstream would have, with the NBN, FTTN delivering up to, say, 50 Mb/s. We consider both these aspects.

We have used only publicly available information in our analysis. For an understanding of NBN deployment plans, we have relied on public statements and reports by the Australian Government and NBN Co. (the government enterprise charged with deploying and operating the NBN), as well as information on current access networks in Australia. For effects on availability, we have started from census data from 2011. Our study uses a bottom-up methodology, estimating broadband changes in small geographical areas and building up a picture for regions and Australia as a whole.

We have concentrated on the time when the NBN has been fully deployed, that is, in the early to mid-2020s and we have restricted our analysis to the NBN fixed-line footprint – that is, excluding areas served by NBN satellites.

Importantly, we have not assumed that fixed-line broadband access would have remained static without the NBN. Rather, we have assumed that there would have been some enhancement of access speeds in response to customer demands. Our exact assumptions are described later in this paper.

For access speeds, in this paper we have concentrated particularly on three breakpoints:

- 10 Mb/s and above downstream and 2.5 Mb/s and above upstream, because the Department of Communications (2013) had found that "a large number of premises" had access to broadband below 9 Mb/s;
- 25 Mb/s downstream and 5 Mb/s upstream, because this is above the maximum access speeds available from ADSL2+;
- 25 Mb/s and above downstream and 10 Mb/s and above upstream, because this is above the maximum upstream access speeds available from FTTN and fixed wireless.

The next section provides an overview of existing broadband access technologies. We then describe our assumptions about broadband in Australia in the long term if the NBN had not happened. This provides a reference case for comparing broadband with the NBN, which is the subject of the following section. We then compare the two futures to determine where and in what way the NBN will make a difference to broadband access availability and access speeds. We summarise our findings in a conclusion.

Fixed Broadband Delivery

In 2013, the Department of Communications (2013) provided a snapshot of broadband access delivery in Australia. For fixed broadband, the most common means of delivery was ADSL over the copper telephony access. More than 90% of premises had access to DSL services; about half those premises had a DSL service in operation (Department of Communications, 2013; ACMA, 2014). An important characteristic of ADSL is that the delivered downstream (and upstream) speed of the service depends on the copper-cable distance between the DSL head-end (most often in a telephone exchange building) and the end customer's premises. The Department's premises-level analysis identified "a large number of premises that can access a basic broadband service only at download speeds less than 9 Mbps", and "many small metropolitan areas where there is limited availability of fixed broadband" (Department of Communications, 2013, p. 4).

In 2013, more than 3 million premises (approximately 28%) had access to fixed-line broadband services other than ADSL. The most widely deployed of these alternatives was cable modem service over the hybrid fibre-coax (HFC), pay-TV networks. HFC has been deployed in the suburbs of major cities and some regional centres. The two largest networks, deployed by Optus and Telstra, overlapped up to about 80% and collectively passed approximately 2.7 million unique premises in metropolitan areas across Adelaide, Brisbane, Gold Coast, Melbourne, Perth and Sydney. An additional 0.7 million premises were in the geographic area bounded by these networks, but were currently not passed (NBN Company, 2013a).

The other fixed broadband technologies had limited deployments. Fibre to the premises (FTTP) was available in central business districts, major business hubs and some recent housing estates; and it continues to be deployed in many new housing estates. Telstra had deployed some Fibre Access Broadband and TransACT had deployed an extensive FTTP network in some Canberra suburbs. The only large-scale deployment of FTTN was the TransACT network in other Canberra suburbs. There were niche deployments of Fixed Wireless (other than for the NBN), mainly for business services.

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Broadband satellite services were and are available to all Australian premises, but they are of limited capacity and are not the most cost-effective way of providing broadband service in metropolitan areas or in most cases where a terrestrial alternative is available. NBN Co. will use broadband satellites to provide service for about 400,000 premises (less than 4% of the total). In our analysis, we have concentrated only on the NBN fixed-line footprint. This will to a small extent underestimate the effects of the NBN.

To build up a picture of broadband availability (with and without the NBN), we have started from "mesh blocks": a "mesh block" is the smallest geographical unit defined by the Australian Statistical Geography Standard (ASGS) for which census data are available from the Australian Bureau of Statistics (ABS, 2013). There were 347,600 mesh blocks covering all of Australia for the 2011 census with a population count of 21.5 million residents. The size of the mesh blocks generally increases as population density decreases. Because of their generally small size, it is possible in many cases to assume that customer premises in a mesh block have access to the same standard of broadband service, except for mesh blocks that cross exchange boundaries, as described below. For each mesh block, there are two data items: the "census population" (hereafter "Residents"), the count of people where they usually live; and the "dwelling counts", the count of structures that are intended to have people live in them and that are habitable. The structure of the ASGS has six hierarchical levels starting from the mesh block up to State and Territory. Each level directly aggregates to the level above and covers all of Australia. That is, a Statistical Area Level 1 (SA1) is an aggregate of Mesh Blocks and SA1s aggregate to Statistical Area Level 2 (SA2), *etc.* Digital boundaries are available for all statistical areas as "Shapefiles" from the ABS (2010).

For the telephony network, we also had data from 2008 of Exchange location points and the boundaries of Exchange Serving Areas (ESAs) and Distribution Area (DAs), available as "Shapefiles" from ExchangeInfo Australia (ExchangeInfo). An ESA defines the area that is served by at least one telephone exchange. The more than 5,000 ESAs come in various shapes and sizes and their areas in regional and remote Australia are much larger than the towns they encompass. An ESA is divided into a number of DAs. Within a DA, which typically covers 100-200 premises, copper cables radiate from a single point (the pillar point) to serve every premises. All geographical information was entered into and processed in QGIS (QGIS Development Team, 2009).

Unfortunately, mesh blocks can cross ESA boundaries. Where a mesh block straddled two or more ESAs, we split it into detailed mesh blocks, one in each ESA. We ended up with 411,400 detailed mesh blocks, in each of which we assumed there would be uniform broadband service delivery. The census data from the original mesh block was divided in proportion to the area of each detailed mesh block. We have allocated other data to the detailed mesh blocks to estimate, for example, how many businesses could benefit from new services and new ways of working that are enabled by the NBN, which is not discussed in this paper.

Once we have established what broadband capabilities will be delivered to each detailed mesh block, we can aggregate up the data to regions, cities or all of Australia.

Fixed broadband availability in the future without the NBN

The NBN incremental availability is subject to broadband access in the long term without the NBN. As before, telecommunications carriers continue to invest in infrastructure. In a future without the NBN, we have assumed that ADSL availability will continue to improve, with all current telephone exchanges equipped with DSLAMs (DSL head-ends) and all planned DAs in Telstra's "top-hat" program being upgraded to ADSL2+, the fastest option. We expect low incentives for telecommunications carriers to expand the footprint of the HFC network, or to significantly increase fibre to the premises and fibre to the node. In particular, we assumed HFC cable networks will be upgraded over time to match the access speeds of the HFC network in the future with the NBN. We also assumed that the access speeds of broadband access technologies such as FTTN and FTTP in their respective coverage will be the same with or without the NBN. In the long term without the NBN we assume no noticeable increase in the coverage of fixed-line broadband access technologies from their pre-NBN actual coverage.

On the basis of the above assumptions, we conducted a spatial analysis of the coverage of the broadband access networks, along with an estimate of the number of residents with access to the access speeds described above.

Asymmetric Digital Subscriber Line 2+ (ADSL2+)

Information about general DSL availability was available from Telstra, including lists of ESAs with telephone exchanges containing a DSLAM (Telstra Wholesale, 2013a), DAs with street cabinets containing a DSLAM (Telstra Wholesale, 2013b), and Telstra's TopHat IP DSLAM Rollout Schedule (Telstra Wholesale, 2013c).

We did not have data on the detailed cable distances to premises. Instead, we have assumed a circular area around an exchange site can be served by DSL at a specified minimum download speed. The radius of this circle varies depending on characteristics such as the ratio of road length to number of addresses and is calculated in two parts. First, the maximum cable distance for the specified minimum download speed is determined from the notional access-speed-versus-distance profile of expected ADSL2+ performance of Telstra's copper network (Clark, 2013). The resulting distances are then reduced to corresponding geographical distances that account for cabling laid in trenches along roads subject to

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region-specific characteristics by using a formula described by the Australian Competition and Consumer Commission (ACCC, 2008). We have adopted the parameters for this function from Analysys (2008) estimated for ESAs that share the same common characteristics. We then used the calculated cable lengths as the radius of the circular coverage area from an exchange in QGIS. This has resulted in smaller and bigger circular coverage areas for all exchange sites depending on the region-specific characteristics. Figure 1 shows examples of circular coverage areas that can be served by DSL at the minimum download speed of 10 Mb/s, which corresponds to a maximum cable distance of 1.7 kilometres.

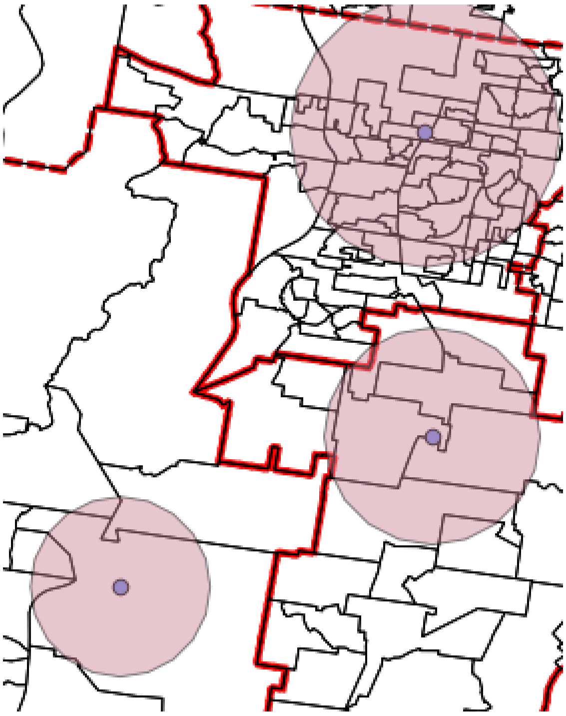

Figure 1: Estimated DSL availability with access to 10 Mb/s and above downstream

Figure 1 shows digital boundaries imported and displayed in QGIS for ESAs in dash lines highlighted in red, and DAs in black solid lines. Locations of exchange sites Greenbank (left bottom corner), Park Ridge (east of Greenbank) and Browns Plains (north of Park Ridge) are displayed in light blue dots. Using the formula with the parameters described by the ACCC, the estimated cable distances and radii for the circular areas around the exchange sites indicated in Figure 1 for the specified minimum download speed are:

- 1.1 km (1.7 km / 1.61) for Greenbank;
- 1.3 km (1.7 km / 1.34) for Park Ridge; and
- 1.6 km (1.7 km / 1.07) for Browns Plains.

In areas where telephone lines are routed via a street cabinet containing a DSLAM, the cable length from the DSLAM in the cabinet to the customer's premises is the critical parameter.

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Exact locations of Telstra street cabinets were not available for this paper. To approximate the locations of cabinets, we used the central point of DSL-enabled DAs instead. We have used the calculated cable lengths as the radius of the circular coverage area from the approximate location of the street cabinets. This may have led to a number of inaccurate circular coverage areas and affected the estimated number of mesh blocks we have identified as a result. We expect the overall effect to be only marginal for two reasons. First, the TopHat upgrades were deployed only in a few cases for a first-in ADSL installation (Telstra Wholesale, 2013c). Second, the parameters of the mesh blocks that unintentionally overlap with incorrectly modelled circular coverage areas will be partly offset by parameters of the mesh blocks that should be included but are not.

For certain upload speeds, to estimate the maximum distance between the customer's premises and the location of the DSLAM, we assumed the download to upload ratio of 4:1 and referred to the practical ADSL2+ download-speed-versus-distance profile from Clark (2013). That is, the estimated cable distances for a minimum upload speed of 2.5 Mb/s will be the same as estimated for a minimum download speed of 10 Mb/s (4 x 2.5 Mb/s) (as in the example above).

We have identified the mesh blocks that intersect with the estimated coverage of the ADSL2+ access network for the minimum access speeds specified above through the use of spatial queries in QGIS. Customer premises in overlapping mesh blocks were treated as having access to the same standard of broadband service as inside the estimated coverage area.

In 305 out of 5069 ESAs, ADSL-enabled DAs were missing from the ExchangeInfo geospatial datasets from 2008. For the 305 ESAs that are affected, we have assumed that ADSL services are available at the maximum access speed throughout the entire ESA. An additional parameter was added to each mesh block indicating whether or not it intersects with any of the 305 ESAs that are affected. Our assumption results in a marginal underestimate of NBN incremental availability outside metropolitan areas, predominantly in the rest of Victoria and Queensland, and Tasmania. It has no effect above ADSL2+ access speeds.

Fibre-to-the-premises (FTTP)

Detailed information of the Telstra Development Sites for Fibre Access Broadband (FAB) was available from Telstra (Telstra Wholesale, 2013d). We have assumed that the FAB as of 15 October 2013 will stay unchanged in the reference case. To identify mesh blocks overlapping Telstra FAB sites in QGIS, we have reduced FAB sites to a single point. That is, we have assumed that the area of a single mesh block overlapping the single point that approximates the location of an FAB site can be served by FTTP. From the report which details the Telstra Development Sites where FAB is available, we extracted the state the FAB

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site resides in, the FAB site name and respective Call Collection Area. We then entered these details for each FAB site in an address-to-a-single-point conversion website. The resulting single points were imported into QGIS to identify the overlapping mesh blocks in a spatial query.

We have also taken the TransACT/iiNet FTTP access network in the Australian Capital Territory into consideration in the reference case. We have assumed that the geospatial datasets of active and "in build" fibre serving area modules (FSAMs) as of December 2013 from myNBN.info [1] include the coverage of the TransACT/iiNet FTTP network in Canberra that was acquired by the NBN Company in November 2013 (NBN Company, 2013b). We then ran a spatial query in QGIS to identify the mesh blocks that intersect with the geospatial datasets of the NBN FTTP network in Canberra.

Hybrid Fibre-Coax (HFC)

HFC network coverage maps were only publicly available for the Optus HFC network (Leong, 2001). Since the Telstra and Optus HFC networks overlap up to about 80% (NBN Company, 2013a), we have used the coverage maps provided in Leong (2001) for an initial estimate of the coverage of the HFC networks in the reference case. We factored in additional coverage described further below. We have imported screen captures of areas covered by the Optus HFC network provided in Leong (2001) into QGIS.

The results of our spatial analysis suggest that, in 2011, more than 6 million people usually lived in less than 2.5 million dwellings that were in the geographic area of mesh blocks covered by the Optus HFC network in Sydney (1.1 million), Melbourne (1 million) and Brisbane (0.4 million). As of 2013, the Telstra and Optus HFC networks collectively pass around 2.7 million premises (NBN Company, 2013a). An additional 0.7 million premises are in the geographic coverage area of the HFC networks, but currently not passed (NBN Company, 2013a). Therefore, we have assumed that, in the geographic area of mesh blocks covered by the Optus HFC network, only about 80% (2.7/(0.7+2.7)) of premises are passed. This corresponds roughly to the actual 2 million households covered by the Optus HFC network according to Leong (2001).

As of 2001, coverage of the Telstra HFC network spanned 2.5 million homes including areas in Perth (Western Australia), Adelaide (South Australia) and the Gold Coast (Queensland) that had no coverage of the Optus HFC access network (Leong, 2001). Given our assumption that most parts of the Optus and Telstra HFC networks overlap in Sydney, Melbourne and Brisbane, about 0.5 million dwellings (2.5 million dwellings covered by the Telstra HFC network minus 2 million dwellings covered by the Optus HFC network) are passed by the Telstra HFC network in Perth (Western Australia), Adelaide (South Australia) and the Gold

Coast (Queensland). To estimate the additional 0.5 million dwellings covered by the Telstra HFC network in those areas, we made reference to the coverage information of HFC by state and territory provided by the Department of Communications (2013).

The Department's analysis found that the number of premises covered by either FTTN or HFC in Western Australia, South Australia and Queensland was 0.1 million, 0.2 million and 0.6 million, respectively (Department of Communications, 2013). Since the only large-scale deployment of FTTN was located outside these three states, we can safely assume that the stated numbers of premises are covered by HFC only. Results from our spatial analysis suggest that about 0.4 million dwellings are located in the geographic area of mesh blocks covered by the Optus HFC network in Brisbane (Queensland). We therefore assumed that 0.2 (0.6-0.4) million dwellings were covered by the Telstra HFC access network in the Gold Coast. The geographic areas by statistical area level 3 (SA3) which we assumed to be covered by the Telstra HFC network in Perth, Adelaide and the Gold Coast are shown in Table 1. Our selection of SA3 was guided by relevant postings in the Australian discussion forums, such as Whirlpool [2], and the estimated total number of dwellings covered by the Optus HFC network.

Table 1: Selected statistical areas (level 3) indicating coverage of HFC access networks in the reference case in Perth, Adelaide and the Gold Coast

Gold Coast	Adelaide	Perth
Broadbeach - Burleigh	Adelaide Hills	Belmont - Victoria Park
Coolangatta	Burnside	Cottesloe - Claremont
Gold Coast - North	Campbelltown (SA)	Melville
Gold Coast Hinterland	Charles Sturt	South Perth
Mudgeeraba - Tallebudgera	Holdfast Bay	
Nerang	Marion	
Ormeau - Oxenford	Mitcham	
Robina	Norwood - Payneham - St Peters	
Southport	Port Adelaide - East	
Surfers Paradise		

In our estimated coverage of HFC access networks in the reference case, we have not included HFC networks in Mildura, Ballarat, Bendigo, Albury-Wodonga, Darwin and Perth (Ellenbrook) because of the comparatively small number of dwellings covered by these networks. This may result in a marginal overestimate of the regional impact of the NBN.

Fibre-to-the-node (FTTN)

Large-scale deployments of FTTN in 2013 only existed in the Australian Capital Territory (Department of Communications, 2013). We have imported screen captures of areas in QGIS covered by FTTP and FTTN networks in Canberra and surrounding areas published by the Department of Communications (2013). We have assumed that the geospatial datasets of the

NBN FTTP network in Canberra from myNBN.info [1] comprise the TransACT/iiNet FTTP network, which NBN Company had acquired in November 2013. We have also assumed that the rest of the imported screen captures comprise the geographic area covered by the FTTN network.

We ran a spatial query in QGIS to identify the mesh blocks that intersect with our estimated coverage of the FTTP and FTTN networks in the Australian Capital Territory. We excluded the mesh blocks that intersect with the geospatial datasets of the NBN FTTP access network in the Australian Capital Territory from the results of the spatial query described above. We assumed that the remaining mesh blocks are covered by the FTTN network in the Australian Capital Territory.

The findings from our spatial analysis of fixed broadband availability in the future without the NBN described in this section feed into a spatial database we have developed for this purpose. For each mesh block, we have included fields for mesh block parameters and access network coverage. In the following section, we describe our spatial analysis of the coverage of the NBN's fixed broadband access networks under the proposed multi-technology approach.

Fixed broadband availability in the future with the NBN

The NBN is being delivered through a mix of existing and future access mechanisms. The NBN fixed-line footprint assumed in this paper comprises the following access mechanisms:

- fibre to the premises where it already exists or was planned as of December 2013;
- hybrid fibre-coax where it already exists and with full coverage of businesses and an expansion to a further 0.7 million premises passed to fill in "black spots";
- fibre to the node with VDSL running on short copper lengths between the "node" and the customers' premises; and
- fixed wireless in less densely populated areas.

Under the proposed multi-technology approach, existing broadband access networks will be upgraded or overbuilt by the NBN. "The eventual mix of technologies will be determined by decisions taken over time for each distribution area, accounting for relevant factors" (NBN Company, 2013a, p. 112).

At the time of our analysis, NBN Company had published (up to June 2014) plans for its fixed-line footprint. Within this footprint, we have assumed that telephone exchange areas not covered by plans for FTTP, HFC or fixed wireless access will be enhanced with FTTN.

Similar to ADSL, the capabilities of FTTN and fixed wireless access depend on transmission distance. For FTTN, we assume that the copper-cable lengths will be short enough to deliver

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at least 25 Mb/s downstream and up to 10 Mb/s upstream. For fixed wireless access, we assume up to 25 Mb/s downstream and no more than 5 Mb/s upstream.

The spatial analysis we have conducted to estimate the coverage of the above broadband access networks is described in the remainder of this section. Our analysis relied on a wide variety of data. Not all of this information refers to the same technology mix. Where reliable data was missing or related to diverging technology mixes, we made assumptions to the best of our knowledge at the time of our analysis.

Hybrid Fibre-Coax (HFC)

The proposed multi-technology approach assumes capacity investments and completing construction of the HFC network to connect all premises within the geographic area that the Telstra and Optus HFC networks cover, that is, 3.4 million total potential HFC premises (NBN Company, 2013a). This includes 0.7 million premises that are in the geographic coverage area of the HFC networks, but currently not passed (NBN Company, 2013a). We have adopted our estimates of the Optus and Telstra HFC networks in the reference case described in the previous section. In these estimates, we had assumed only about 80% of residences were passed in the coverage areas. For the NBN, we assume that the remaining 20% (0.7/3.4) of residences are covered, and hence the additional 20% of the relevant residential parameters of intersecting mesh blocks account for the NBN impact on service delivery.

Fibre-to-the-premises (FTTP)

Under the proposed multi-technology approach, FTTP could cover between 20% and 26% of premises in the fixed line footprint (NBN Company, 2013a). To estimate the coverage of the NBN FTTP network, we conducted a spatial analysis of geospatial datasets of current and planned FTTP deployments as of December 2013 from myNBN.info [1]. We have assumed that the coverage of the NBN FTTP network is the geographic area of the mesh blocks that intersect with the NBN FTTP geospatial datasets, excluding the geographic area of the mesh blocks covered by HFC deployments. Since we have used data from various sources over a time period in which the proposed technology mix of the NBN has changed several times, we have excluded FTTP coverage areas where they overlap with our estimated coverage area of HFC.

Fibre-to-the-node (FTTN)

Under the proposed multi-technology approach, most of Telstra's copper network will be overbuilt by FTTN covering about half of all premises in the fixed-line footprint (NBN Company, 2013a). The originally proposed fixed-line footprint was defined by NBN

Company by a list of localities that would have received some fibre coverage (NBN Company, 2010). We have assumed that the originally proposed fixed-line footprint is identical to the one proposed under the multi-technology approach. We took the list of localities and identified each locality's geographic location. To do this, we relied on a mapping of place names to geography. The naming convention in the lists of localities best matches the one used for the statistical areas of 2006 Urban Centres and Localities (ABS, 2007). We then assumed that the ESAs in these locations would be covered by FTTN, but we excluded any areas already identified as receiving FTTP or HFC deployments.

Fixed Wireless

The proposed multi-technology approach assumes that about 6% of premises outside the NBN fixed-line footprint will be covered by fixed wireless and satellite technologies. Our estimates of the coverage of the NBN fixed wireless network relied on three data sources. First, we used geospatial datasets of active and "in build" Wireless Serving Areas as of December 2013 from myNBN.info [1] to find all mesh blocks that are fully or partially in the serving areas. At the edges, for any mesh block that is only partially covered by the serving area, we included the parameters in proportion to the covered area as a fraction of the total area of the mesh block. This has resulted in 226,478 residents in the estimated area covered by fixed wireless, or about 46% of the 494,515 total residents in the area of overlapping mesh blocks. We use this ratio below to estimate the coverage effect of fixed wireless.

When processing the geospatial datasets in QGIS, we found that the average coverage of NBN Wireless Serving Areas spans approximately the average size of an SA2. We therefore assumed that the SA2 with a matching name among the localities in the updated list of Wireless Serving Areas published on the independent NBN tracking website (Finder.com.au), our second data source, corresponds to the coverage area of the NBN fixed wireless access. Our third data source was a list of localities that would have received some wireless coverage under the originally proposed wireless footprint defined by NBN Company (2010). We took the list of localities and identified each locality's geographic location similar to the approach described above. We then assumed that the ESAs in these locations would also be covered by fixed wireless. Using our estimated ratio calculated above, however, we have assumed that only about 46% of the parameters associated with mesh blocks that overlap the selected SA2s and ESAs are included in our estimate of the effects of the NBN fixed wireless deployments. In all cases, we have excluded any areas already identified as receiving FTTP, HFC or FTTN deployments.

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Comparison of Futures with or without the NBN

In this section, we determine where and in what way the NBN will make a difference to fixed broadband access availability and access speeds compared to the future without the NBN. For the comparison of futures with or without the NBN, we have aggregated up the estimated number of residents in geographical regions with access to selected downstream and upstream speeds to greater capital city statistical areas (GCCSAs). GCCSAs do not cover just the built-up edge of the city but also include people who live in small towns and rural areas surrounding the city but who regularly socialise, shop or work within the city, according to the 2011 Census travel-to-work data. The area not defined as being part of the Greater Capital City within each State and Territory is represented by a Rest of State region. Table 2 shows the estimated number of residents in geographical areas with access to 10 Mb/s and above downstream and 2.5 Mb/s and above upstream in the futures with or without the NBN.

Table 2: Estimated number of residents in geographical areas with access to 10 Mb/s and above downstream and 2.5 Mb/s and above upstream

Region	Access with no NBN (No. of residents)	Improvement with the NBN (No. of residents)	Improvement with the NBN (% of all residents)
Greater Sydney	3,699,864	593,853	13.5%
Rest of New South Wales	1,807,639	533,334	21.2%
Greater Melbourne	3,155,074	790,888	19.8%
Rest of Victoria	932,876	311,546	23.2%
Greater Brisbane	1,717,295	325,799	15.8%
Rest of Queensland	1,886,756	257,014	11.4%
Greater Adelaide	1,023,088	178,648	14.6%
Rest of South Australia	233,951	78,031	21.2%
Greater Perth	1,452,299	270,637	15.7%
Rest of Western Australia	348,023	86,007	17.1%
Tasmania	263,359	206,654	41.8%
Northern Territory	159,116	31,504	15.0%
Australian Capital Territory	289,111	549	0.2%
Total	**16,968,451**	**3,664,463**	**17.1%**

The second column in Table 2 shows the estimated number of residents in geographical areas with access to the selected access speeds in the future with no NBN. In accordance with the findings from the Department of Communications that “a large number of premises” had access to broadband below 9 Mb/s, our results suggest that almost 80% of all residents would have had access to relatively modest access speeds in the absence of the NBN. This can be explained by the large number of premises with access to DSL services and our assumption that ADSL availability will continue to improve, resulting in all current telephone exchanges equipped with DSLAMs and all planned DAs in Telstra’s “top-hat” program being upgraded to ADSL2+. Our results shown in the third and fourth columns in Table 2 suggest that the improvement in the future with the NBN in most regions is less than 20% except in rest of New South Wales, rest of Victoria, rest of South Australia and Tasmania (where more than 40% of residents benefit from the NBN).

Figures 2 and 3 show the geographical areas of improvement in availability and access speeds compared to the future with no NBN in Greater Melbourne and Greater Sydney. The geographical areas highlighted in yellow show the improvement in broadband availability and access speeds with the NBN. The geographical areas highlighted in yellow and black dots indicate the improvement with the NBN in the HFC footprint for a proportion of residents. The Greater Capital City boundaries are shown by the red dash line.

Figures 2 and 3 show that the improvement in availability and access speeds is particularly marked in outer suburban areas between the exchanges around the circular coverage areas of ADSL2+ access networks in the future without the NBN.

Our estimated numbers of residents in geographical areas with access to downstream and upstream speeds above the maximum available from ADSL2+ are shown in Table 3.

Table 3: Estimated number of residents in geographical areas with access to 25 Mb/s downstream and 5 Mb/s upstream [revised July 2018—see Endnote 3]

Region	Access with no NBN (No. of residents)	Improvement with the NBN (No. of residents)	Improvement with the NBN (% of all residents)
Greater Sydney	2,266,008	2,013,932	45.9%
Rest of New South Wales	401	2,250,005	89.5%
Greater Melbourne	1,821,904	2,113,784	52.8%
Rest of Victoria	-	1,141,018	84.8%
Greater Brisbane	760,945	1,267,102	61.3%
Rest of Queensland	402,678	1,652,720	73.3%
Greater Adelaide	409,504	790,409	64.5%
Rest of South Australia	-	285,776	77.6%
Greater Perth	212,467	1,508,464	87.3%
Rest of Western Australia	314	398,417	79.3%
Tasmania	-	458,606	92.8%
Northern Territory	-	161,344	76.8%
Australian Capital Territory	221,291	612	0.2%
Total	**6,095,513**	**14,042,189**	**65.4%**

The numbers in the second column of Table 3 show the numbers of residents who, without the NBN, could access broadband via HFC, FTTN or FTTP. This is less than 40% of all residents of Australia. The estimated improvement in the future with the NBN is significant in most regions except Australian Capital Territory where a comparatively large number of residents is concentrated in geographical areas served by FTTP or FTTN in the future with no NBN.

Figure 2: Estimated improvement in availability and access speeds in geographical areas in Greater Melbourne with access to 10 Mb/s and above downstream and 2.5 Mb/s and above upstream

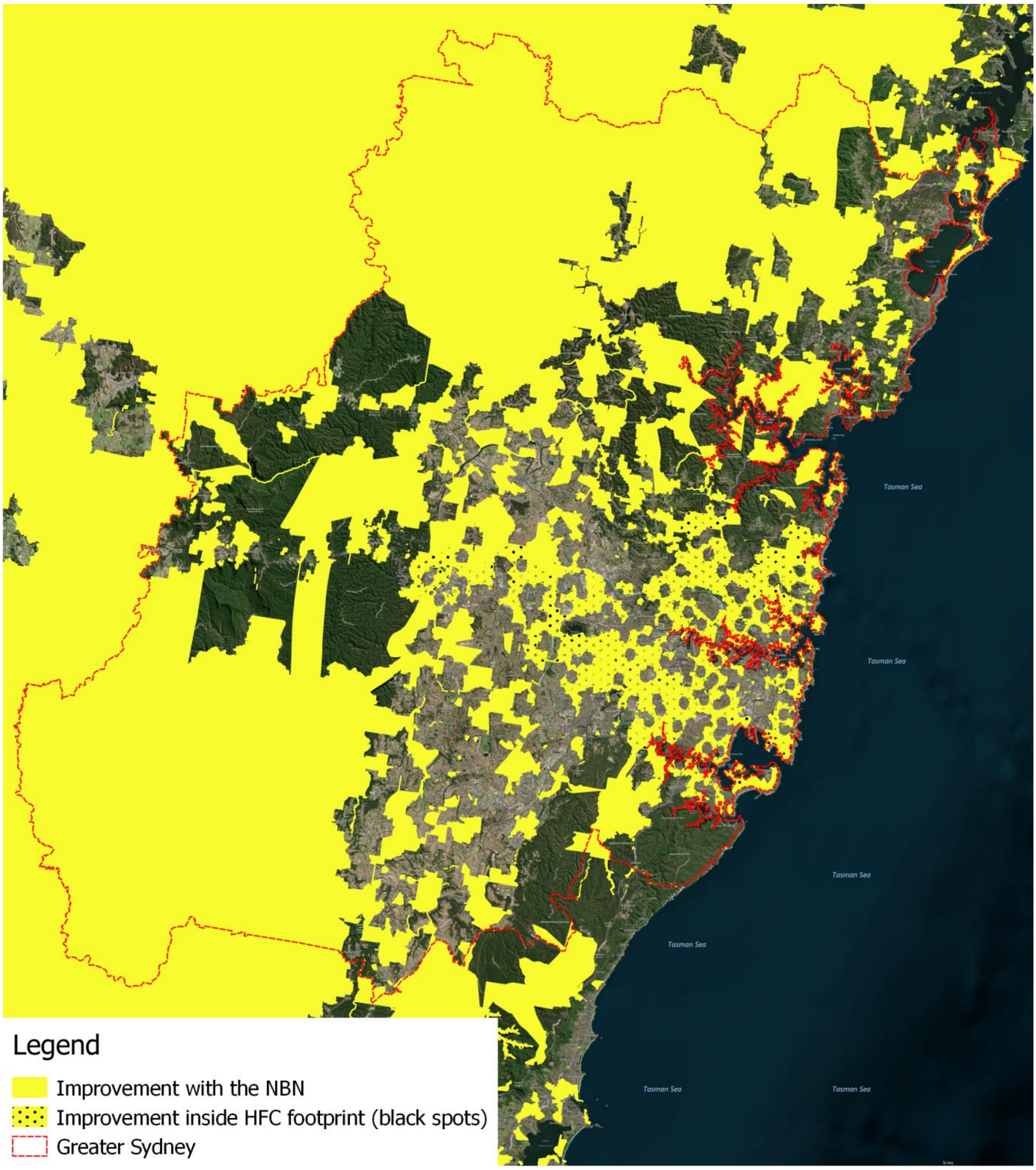

Figure 3: Estimated improvement in availability and access speeds in geographical areas in Greater Sydney with access to 10 Mb/s and above downstream and 2.5 Mb/s and above upstream

Figures 4 and 5 show the geographical areas of improvement in availability and access speeds compared to the future with no NBN in Greater Melbourne and Greater Sydney.

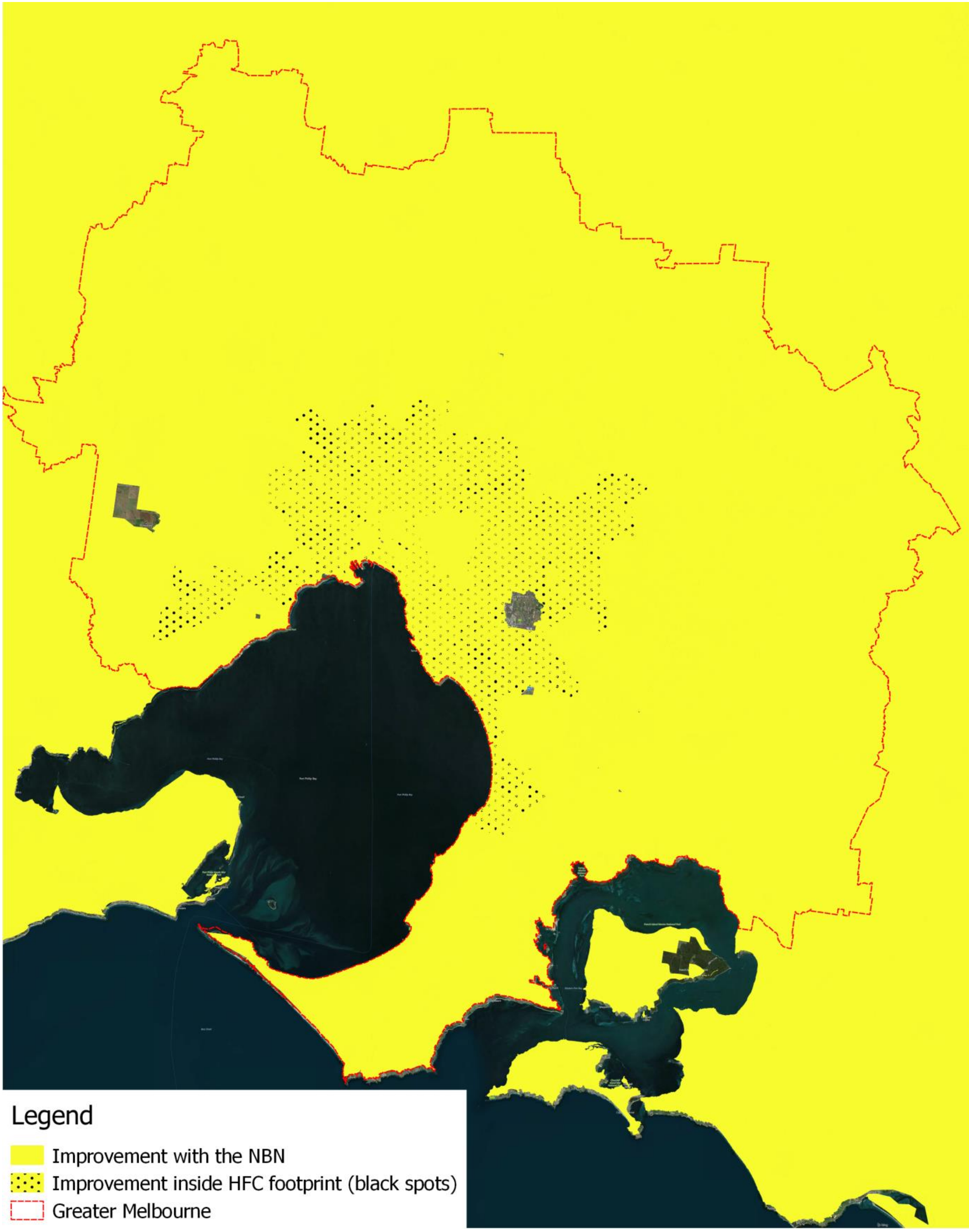

Figure 4: Estimated improvement in availability and access speeds in geographical areas in Greater Melbourne with access to 25 Mb/s downstream and 5 Mb/s upstream

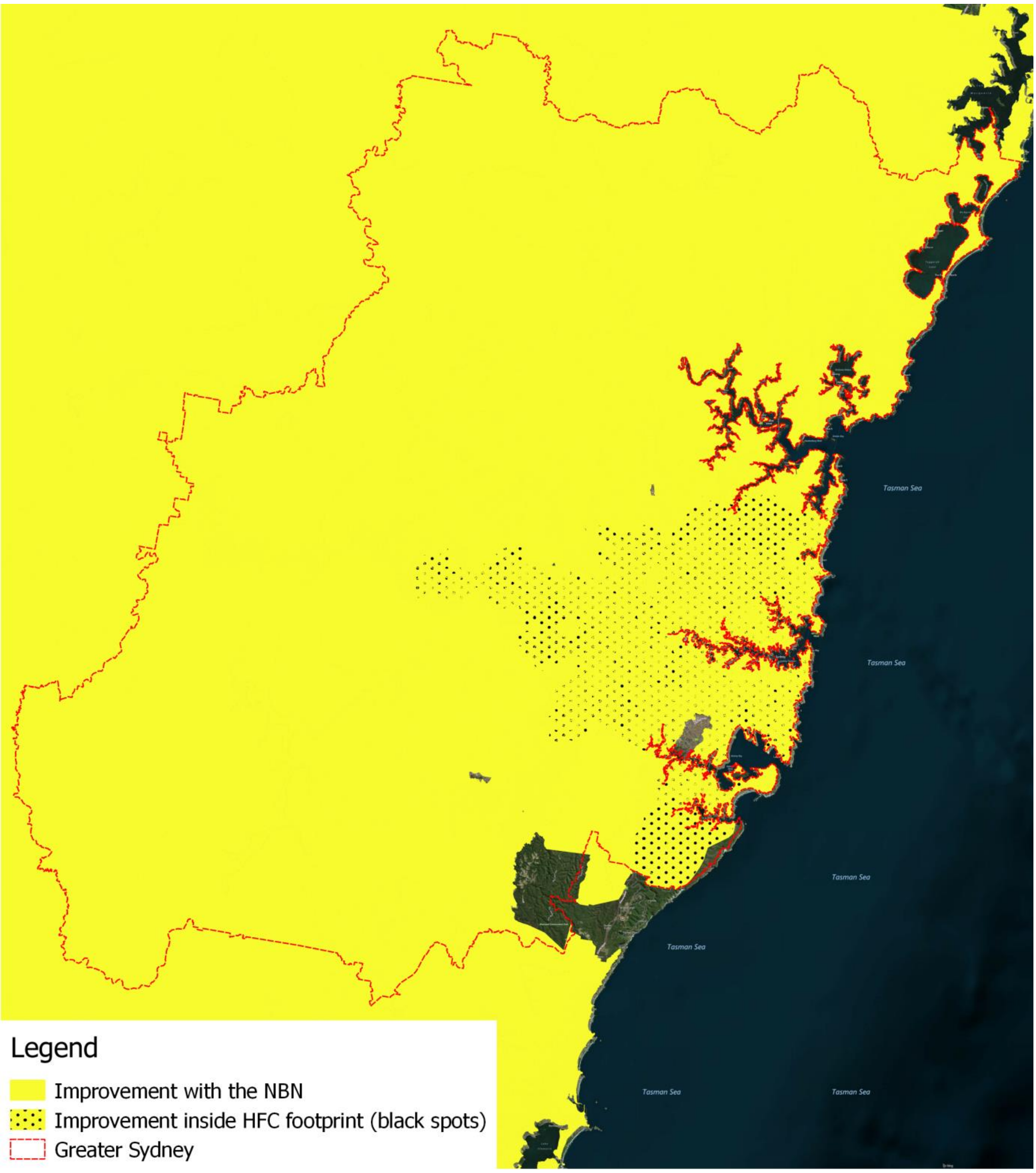

Figure 5: Estimated improvement in availability and access speeds in geographical areas in Greater Sydney with access to 25 Mb/s downstream and 5 Mb/s upstream

Figures 4 and 5 show the consistent improvement in availability and access speeds in Greater Melbourne and Greater Sydney, affecting approximately half of the regions' population.

Our estimated numbers of residents in geographical areas with access to downstream and upstream speeds above the maximum available from ADSL2+, FTTN and fixed wireless are shown in Table 4.

Table 4: Estimated number of residents in geographical areas with access to 25 Mb/s and above downstream and 10 Mb/s and above upstream [revised July 2018—see Endnote 3]

Region	Access with no NBN (No. of residents)	Improvement with the NBN (No. of residents)	Improvement with the NBN (% of all residents)
Greater Sydney	2,266,008	687,499	15.7%
Rest of New South Wales	401	118,991	4.7%
Greater Melbourne	1,821,904	603,367	15.1%
Rest of Victoria	-	43,558	3.2%
Greater Brisbane	760,945	248,512	12.0%
Rest of Queensland	402,678	231,683	10.3%
Greater Adelaide	409,504	148,078	12.1%
Rest of South Australia	-	0	0.0%
Greater Perth	212,467	74,545	4.3%
Rest of Western Australia	314	13,246	2.6%
Tasmania	-	116,175	23.5%
Northern Territory	-	39,732	18.9%
Australian Capital Territory	37,859	0	0.0%
Total	**5,912,081**	**2,325,386**	**10.8%**

While less than 40% of residents have access to higher access speeds in the future without the NBN, the improvement in availability and access speeds with the NBN is only about 11% of all residents. The improvement is comparatively small because the proposed mixed technology approach of the NBN includes FTTN and fixed wireless access networks that do not meet higher access-speed requirements. In particular, a relatively large number of premises in the NBN fixed-line footprint is served by the FTTN access network. ADSL is 'asymmetric' in that data rates are higher in the downstream direction (toward the end-user) compared to the upstream direction (toward the network). FTTN does provide 25 Mb/s and above downstream but does not provide 10 Mb/s and above upstream. A large number of residents in regional and urban areas therefore do not have access to higher upstream speeds with the NBN.

Figures 6 and 7 show the geographical areas of improvement in availability and access speeds compared to the future with no NBN in Greater Melbourne and Greater Sydney.

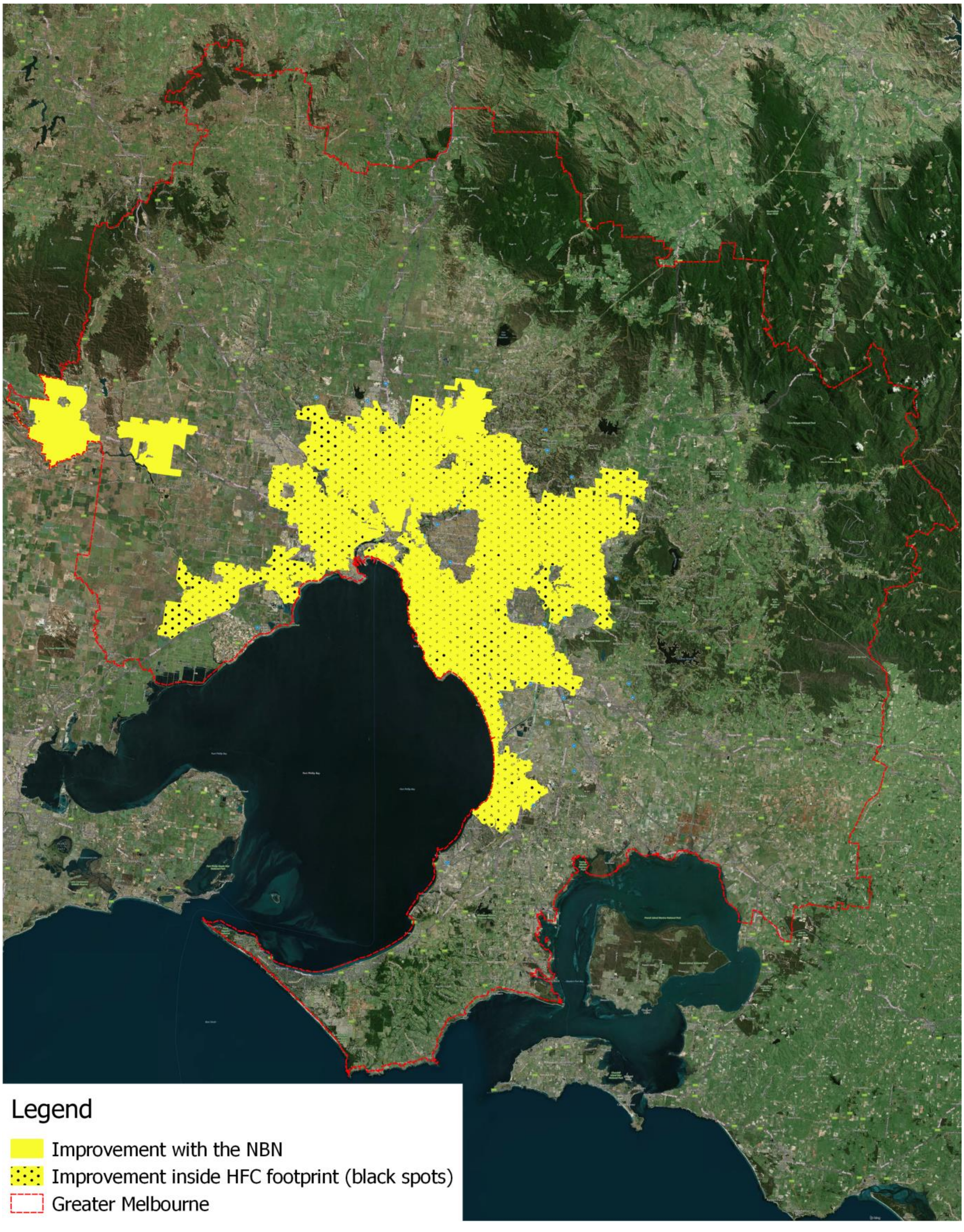

Figure 6: Estimated improvement in availability and access speeds in geographical areas in Greater Melbourne with access to 25 Mb/s and above downstream and 10 Mb/s and above upstream

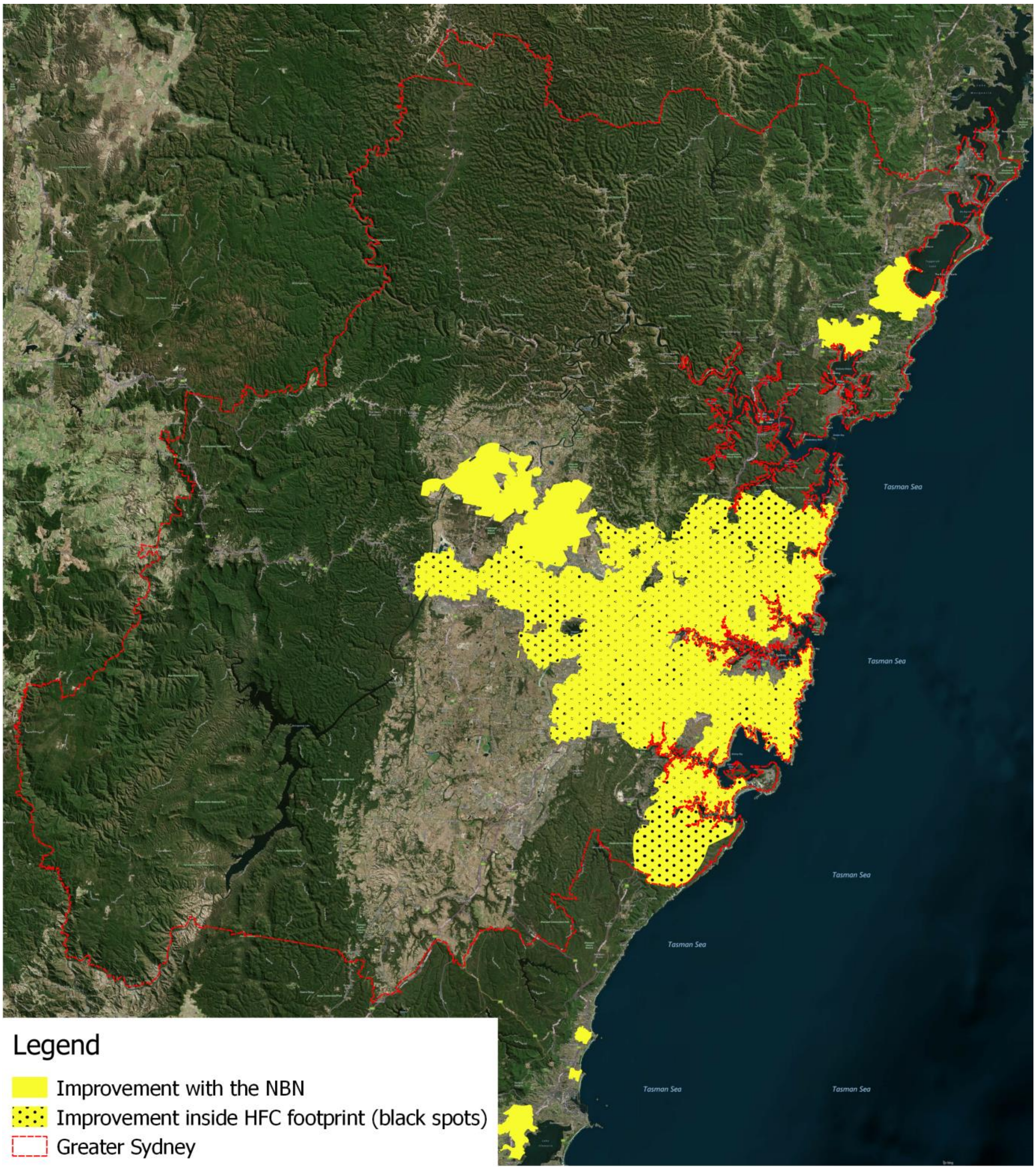

Figure 7: Estimated improvement in availability and access speeds in geographical areas in Greater Sydney with access to 25 Mb/s and above downstream and 10 Mb/s and above upstream

Figures 6 and 7 show that the improvement in availability and access speeds is significantly smaller and concentrated in the HFC footprint and geographical areas served by the FTTP access network.

For a regional example, Figure 8 shows the improvement in availability and access speeds compared to the future without the NBN in Tamworth, New South Wales, highlighted in yellow. The city of Tamworth is located in Inner Regional Australia and is served by a mix of NBN Wireless Serving Areas and FTTN access network. The boundary of the Tamworth ESA is shown with a red dotted line. The improvement in availability and access speeds with access to 10 Mb/s and above downstream and 2.5 Mb/s and above upstream is shown on the left, 25 Mb/s downstream and 5 Mb/s upstream in the middle, and 25 Mb/s and above downstream and 10 Mb/s and above upstream on the right.

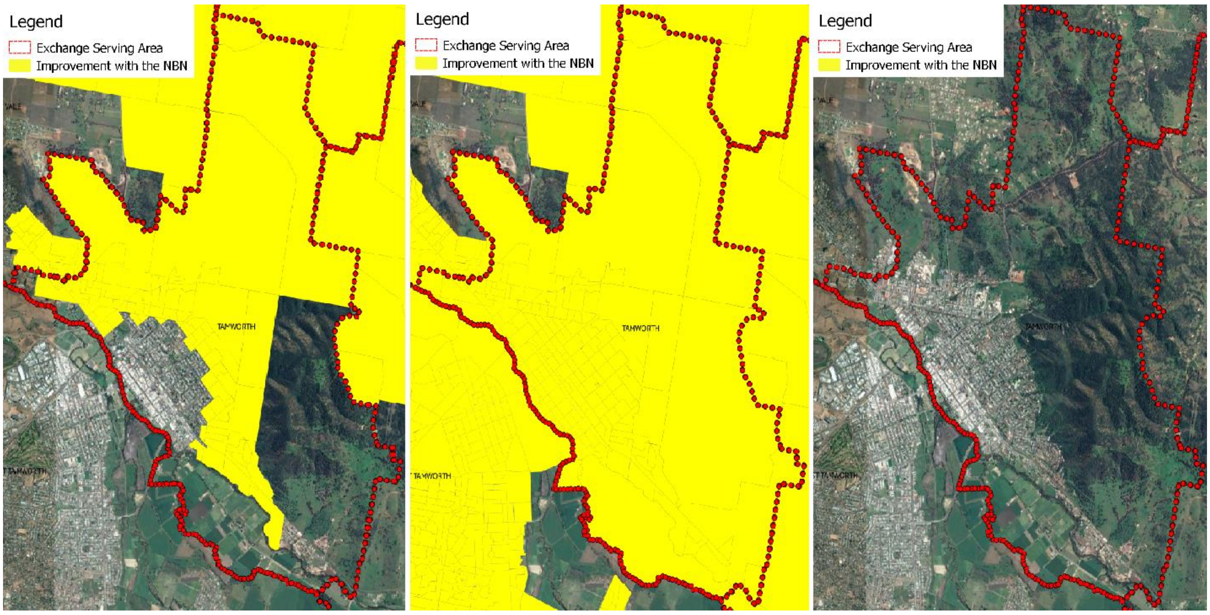

Figure 8: Estimated improvement in availability and access speeds in geographical areas in Tamworth, New South Wales

Our results suggest that with the NBN the improvement in availability and access speeds of 10 MB/s and above downstream and 2.5 Mb/s and above upstream shown on the left affects more than half of the population served by the Tamworth exchange. All residents benefit from the improvement in availability and access speeds above the maximum available from ADSL2+, shown in the middle. There is no improvement in availability and access speeds of 25 Mb/s and above downstream and 10 Mb/s and above upstream with the NBN, shown on the right.

Conclusions

The study presented in this paper is based on results of a spatial analysis of fixed broadband availability in the futures with or without the NBN. We have used the smallest geographical unit for which census data are available. Our assumptions about broadband in Australia in the long term if the NBN had not happened provide a reference case for comparing broadband with the NBN.

In the period after the current NBN has been fully deployed, the NBN makes only a marginal improvement in the availability of *any* fixed-line broadband. This is because, even without the NBN, more than 90% of premises have access to DSL.

The picture for access speeds, however, is different and the NBN will provide a significant enhancement. The improvement in access speeds is particularly marked in outer suburban areas between the exchanges around the coverage areas of ADSL2+ access networks in the future without the NBN. Even for the relatively modest 10 Mb/s downstream, which could be provided by ADSL2+, the NBN will make a difference: a further 17% of the population will have access to 10 Mb/s downstream in most regions and in particular regional areas of New South Wales, Victoria, South Australia and Tasmania. A further two-thirds of the population will have access to speeds above the maximum access speeds available from ADSL2+.

The improvement in access speeds in the upstream direction (toward the network) is significantly hampered by asymmetric access networks with limited capabilities in terms of data rates. Only a further 11% of the population will have access to 10 Mb/s and above upstream.

While the maximum access speeds available in the fixed-line footprint might be sufficient for telework and telehealth services, the availability of services requiring 10 Mb/s and above upstream will be limited with the Multi-Technology Mix version now being deployed. To meet the speed requirements of advanced cloud computing services, for example, FTTN could be upgraded in the future, providing potential economic benefits to business (KPMG, 2012).

References

Analysys (2008), Fixed LRIC cost model documentation, Model documentation for the Australian Competition and Consumer Commission, 17 December 2008.

Australian Bureau of Statistics (2007), Australian Standard Geographical Classification (ASGC) Urban Centres and Localities (UC/L) Digital Boundaries, Australia, 2006, Catalogue number 1259.0.30.003, 21 August 2007, (online) www.abs.gov.au, Available from: www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/1259.0.30.003Main+Features12006 (Accessed 8 February 2018)

Australian Bureau of Statistics (2010), Australian Statistical Geography Standard (ASGS): Volume 1 - Main Structure and Greater Capital City Statistical Areas, July 2011 , Catalogue number 1270.0.55.001, 23 December 2010, (online) www.abs.gov.au, Available from: http://www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/1270.0.55.001Main+Features1July 2011 (Accessed 8 February 2018)

Australian Bureau of Statistics (2013), Mesh Block Counts, 31 July 2013, (online) www.abs.gov.au, Available from: http://www.abs.gov.au/websitedbs/censushome.nsf/home/meshblockcounts (Access on 13 February 2017)

Australian Communications and Media Authority (2014), ACMA Communications report 2013-14, 5 November 2014.

Australian Competition and Consumer Commissions (2008), 'Analysys cost model for Australian fixed network services', Discussion Paper, December 2008.

Clark, R. (2013), 'Fibre to the Most Economic Point', Presentation at CommsDay Melbourne Congress, 10 October 2013, (online) www.slideshare.net, Available from: https://www.slideshare.net/CommsDay/alcatel-lucents-ric-clark (Accessed 19 November 2017)

Department of Communications (2013). 'Broadband Availability and Quality Report', December 2013.

ExchangeInfo Australia, (online) www.pitneybowes.com, Available from: https://www.pitneybowes.com/au/data/boundary-data/exchange-info-australia.html (Accessed 29 November 2017)

Finder.com.au (online) https://www.finder.com.au, Available from: https://www.finder.com.au/nbn-tracker/rollout/list (Accessed 8 February 2018)

KPMG (2012), 'Modelling the Economic Impact of Cloud Computing', Australian Information Industry Association, April 2012.

Leong, J. (2001), 'Telecommunication infrastructures in Australia 2001', A Research Report prepared for ACCC, Technology Applications Group, BIS Shrapnel, December 2001.

NBN Company (2010). (online) http://www.nbnco.com.au

NBN Company (2013a). 'Strategic Review', 12 December 2013.

NBN Company (2013b). 'NBN Co welcomes ACCC clearance of TransACT/iiNet deal', 14 November 2013, (online) https://www.nbnco.com.au, Available from: https://www.nbnco.com.au/corporate-information/media-centre/media-releases/nbn-co-welcomes-accc-clearance-of-transact-iinet-deal.html (Accessed 8 February 2018)

QGIS Development Team (2009). QGIS Geographic Information System. Open Source Geospatial Foundation, (online) https://www.qgis.org, Available from: https://www.qgis.org/de/site/ (Accessed 8 February 2018)

Telstra Wholesale (2013a). ADSL2+ Enabled Exchanges, Version 1032, 29 July 2013, (online) https://www.telstrawholesale.com.au, Available from: http://telstrawholesale.com.au/products/broadband/adsl/adsl-reports-plans/index.htm (Accessed 13 May 2014)

Telstra Wholesale (2013b). ADSL Enabled & Proposed Enabled Distribution Area Report, Version 432, 31 July 2013, (online) https://www.telstrawholesale.com.au, Available from: http://telstrawholesale.com.au/products/broadband/adsl/adsl-reports-plans/index.htm (Accessed 22 October 2013)

Telstra Wholesale (2013c). IP DSLAM Rollout Schedule Report, 2 September 2013, (online) https://www.telstrawholesale.com.au, Available from: http://telstrawholesale.com.au/products/broadband/adsl/adsl-reports-plans/index.htm (Accessed 17 October 2013)

Telstra Wholesale (2013d). FTTP Sites for FAB, 15 October 2013, (online) https://www.telstrawholesale.com.au, Available from: https://www.telstrawholesale.com.au/products/broadband/fibre-access-broadband.html (Accessed 22 September 2014)

Endnotes

[1] Copies of digital boundaries for all Fibre and Fixed Wireless footprints active and in build as of December 2013 received from the creator and developer of the independent tracking website www.mynbn.info which has moved to the website www.finder.com.au in February 2016.

[2] For a discussion on Telstra HFC network coverage in Perth, see, for example, the website under the following link (last accessed on 26 February 2017): https://forums.whirlpool.net.au/archive/1931824.

[3] This paper was revised in July 2018 to correct the values for the number of residents with 'Access with no NBN' in Tables 3 and 4.

Handover with Buffering for Distributed Mobility Management in Software Defined Mobile Networks

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Abstract: The rapidly-growing number of mobile subscribers has led to the creation of a large number of signalling messages. This makes it difficult to efficiently handle the mobility of subscribers in mobile cellular networks. The long-term evolution (LTE) architecture provides software-defined networking (SDN) to meet the requirements of 5G networks and to forward massive mobile data traffic. The SDN solution proposes separation of the control and data planes of a network. Centralized mobility management (CMM) is widely used in current mobile network technologies, such as 4G networks. One of the problems related to CMM is a single point of failure. To solve the problems of CMM and in order to provide for efficient mobility management, IETF has developed a solution called distributed mobility management (DMM), in which mobility is handled via the nearest mobility anchor. In this paper, we propose a DMM solution with handover operations for SDN-enabled mobile networks. The advantage of the proposed solution is that intra and inter handover procedures are defined with the data buffering and forwarding processes between base stations and mobility anchors. We adopt a simulation model to evaluate and compare the proposed solution with the existing solution in terms of handover latency, packet loss and handover failures.

Keywords: DMM, handover, LTE, SDN.

Introduction

The requirements of 5G networks have led to challenges for mobile network operators. These challenges include increasing the development speed of mobile networks and their

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technologies, such as increase in the number of mobile subscribers, signalling messages, and mobile traffic and integration of different technologies, social application data, and live video streaming (Cisco 2017). In addition, efficient management of the mobility of User Equipment (UE) is an important issue. Operators have been developing new solutions to improve network performance and manage it efficiently, such as Network Function Virtualization (NFV), Software-Defined Network (SDN), Distributed Mobility Management (DMM), cloud computing, and network clustering.

To meet the requirements of 5G networks, new paradigms, such as SDN, have been introduced by researchers and organizations for mobile network architecture (Ameigeiras 2015, Costa-Requena 2015, Kyung 2015). In SDN, control and data planes are separated using software such as the OpenFlow protocol (ONF 2012). The control plane is logically centralized by a software controller that can control OpenFlow-protocol-enabled network devices and their data routing/transmission processes to maintain low cost and high network performance. The software controller transforms the data plane into a virtual network over the physical network topology. The controller can configure the forwarding tables for OpenFlow-protocol-enabled network devices and monitor the performance of the data plane (ONF 2012).

In current LTE networks, centralized mobility management (CMM) is widely used to manage UE's mobility, to locate subscribers, and to control the data transmission paths. However, the primary problem of CMM is a single point of failure. Signalling data storms are one of the challenges in CMM. To solve the abovementioned problems, DMM is being developed by the Internet Engineering Task Force (IETF) (2016) to handle UE's mobility and manage mobile flows via the nearest anchor of the distributed mobility management entity (DMME) at the edge of a network.

The advantages of integrating SDN and DMM are that procedures and development are faster and redesigning is easier compared to CMM (Ernest 2013, Giust 2015). In Nguyen (2015), the authors propose hybrid mobility management, which is a combination of DMM and Proxy Mobile IPv6 (PMIPv6) (Perkins 2011). This method can reduce the handover latency of the DMM solution. The layer-2 handover procedures supported by the DMM solution are presented in Sanchez (2016). Local controllers are defined for the intra handovers in the area of mobility anchors, and regional controllers are defined for the inter handovers between different PDN gateways (P-GWs).

In this work, we propose a Handover with data Buffering and Forwarding (HoBF) to improve handover performance. In the proposed HoBF, the definition of intra handover is the same as the X2 handover in LTE networks. Inter handover is defined in the following two parts:

(1) X2 handover with the data buffering and forwarding processes between base stations; (2) the serving and target mobility anchors exchange the information of a UE for data buffering/forwarding between DMMEs and for updating the transmission path via an SDN controller. In addition, we develop a simulation model for the proposed HoBF and the handover procedures in SDN/LTE networks.

The rest of the paper is organized as follows: Section II reviews related work and recent proposals. Section III describes our proposed HoBF considered in this study. The simulation setup and results are described in Section IV. In Section V, conclusions are presented.

Related Work

In the last few years, several studies have been carried out on adopting DMM in mobile networks. In Ernest (2013) and Giust (2015), the authors introduce the advantages of integrating SDN and DMM: i.e., faster procedures and development and easier redesign compared to CMM. Furthermore, in Nguyen (2015), the authors propose hybrid mobility management, which is a combination of DMM and PMIPv6. In Sanchez (2016), the authors propose a DMM solution with a local controller for intra handover and a regional controller for inter-domain handover.

Several researchers have proposed novel SDN-based DMM approaches (Nguyen 2016, Yang 2016, Ko 2017, Kukliński 2014). In Ko (2017), the authors propose an SDN-based approach for DMM that implements the location and handover management functions at a centralized SDN controller, while the packet-forwarding function is fully distributed at access routers. Therefore, SDN-based DMM can accomplish packet forwarding path optimization and provide significant benefits in terms of network and traffic management.

In Nguyen (2016), the authors introduce a method of using SDN-based DMM in 5G networks and compare the existing DMM proposals with the proposed SDN-based DMM. The authors placed their proposed DMM on top of an SDN controller as an application server. The result of this solution shows that complexity of the control plane decreases and becomes more scalable in terms of handover procedure delay and transmission delay.

In Valtulina (2014), the author introduces and evaluates a novel SDN/OpenFlow-based DMM approach that can be applied in virtualized LTE systems. In the proposed approach, the X2 interface is used for handover procedure between P-GWs, and network traffic can be seamlessly continued by a target P-GW. Simulation results show that the handover time is less than 150 ms. It can provide the requirement of LTE and LTE-A networks.

In Wang (2014), the author presents a survey result to improve the existing PMIPv6 mobility management protocol using DMM. In Giust (2014), the authors develop an analytic model of the handover latency of PMIPv6 and its distributed solution. They use the results obtained from analytic and experimental performance to evaluate the benefits of deploying a DMM solution. In Lee (2012), the authors present a novel protocol for IP mobility support. This protocol is referred to as a host-based DMM in the current mobile networks. In addition, they compare the performance of their protocol and Mobile IPv6 in terms of throughput and handover latency. Lee analyses and compares existing IPv6 mobility management protocols in Lee (2013), including the recently standardized PMIPv6 and fast PMIPv6. Lee and his co-authors analyse the performance of IPv6 mobility management protocols in terms of handover latency, handover blocking probability, and packet loss, and provide a few numerical results.

In Nguyen (2013), the author proposes a solution to improve existing PMIPv6 using a DMM-based inter-domain mobility scheme. This solution brings the mobility anchors near to the access network and provides mobility service to the nearby area of the gateway that genuinely requires continuous service. The partially distributed solution shows better performance than other solutions.

Handover management for Distributed Mobility Management

In this section, we describe the proposed HoBF for DMM in SDN-enabled mobile networks. When UE enters the service area of another P-GW, UE executes S1 handover procedure between serving and target P-GWs if the IP address is changed. During S1 handover, a two-level buffering scheme is used from serving cell to target cell and serving P-GW to target P-GW. The existing IETF solution uses the S1 handover of LTE networks with some changes only to enable the OpenFlow protocol.

The LTE network model for our solution is shown in Figure 1. As seen in the figure, base stations are connected to a nearby P-GW (S1 interface). These base stations are referred to as cluster eNodeBs in LTE networks. An eNodeB is connected to the nearest eNodeB through the X2 interface and logically connected to the management section of the network through the S1 interface. P-GWs are distributed for different areas of the network to control and operate the data plane and routing and transmission paths. An S-GW routes data between P-GWs and external networks.

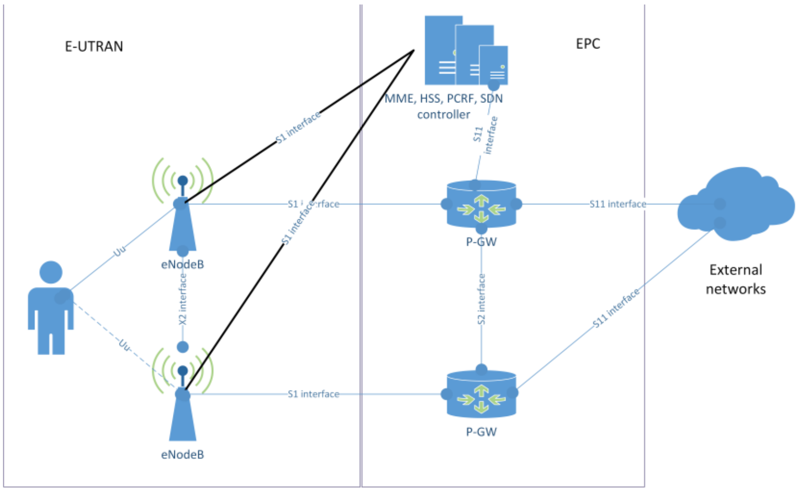

Figure 1. SDN enabled LTE network architecture with DMM solution

In the proposed HoBF, a P-GW can handle the mobility of UEs and manage the handover procedures instead of the CMM located in the management section of the Evolved Packet Core (EPC). A P-GW manages an IP address, which is referred to as the home address, for the UEs that establish a connection via eNodeBs. The UE does not change the IP address during the X2 handover of the LTE network when it moves to the target eNodeB (when the serving and target eNodeBs are attached to the same P-GW). This is referred to as intra mobility in the area of the P-GW. On the contrary, the IP address of the UE that moves to the target eNodeB of another P-GW changes during the S1 handover procedures. In other words, the UE enters the area of a different P-GW and executes the S1 handover procedures between neighbouring P-GWs.

After the handover procedures are performed successfully, the SDN controller configures the routing table between the serving and target P-GWs to provide a continuous session. Then, the SDN controller updates the routing table of the switches for a new path between the UE and external networks. Finally, the SDN controller releases radio resources and the old IP address based on the disconnection request by the serving P-GW. However, before this release process, two IP addresses (different P-GWs) can provide simultaneous connections for the UE, and data buffering and retransmission processes are performed between eNodeBs or P-GWs. The next subsection describes the two handover procedures.

Intra X2 Handover procedures

In this subsection, we describe the X2 handover procedures in the proposed HoBF. Network based X2 handover is executed at nearby eNodeBs when the UE moves to the attached P-GW; this is the same as in LTE networks (Nguyen 2016). Figure 2 shows the X2 handover procedure with the buffering and packet forwarding steps. During the handover procedure, the packets received at an old eNodeB are buffered and forwarded to new eNodeBs after the handover is successful.

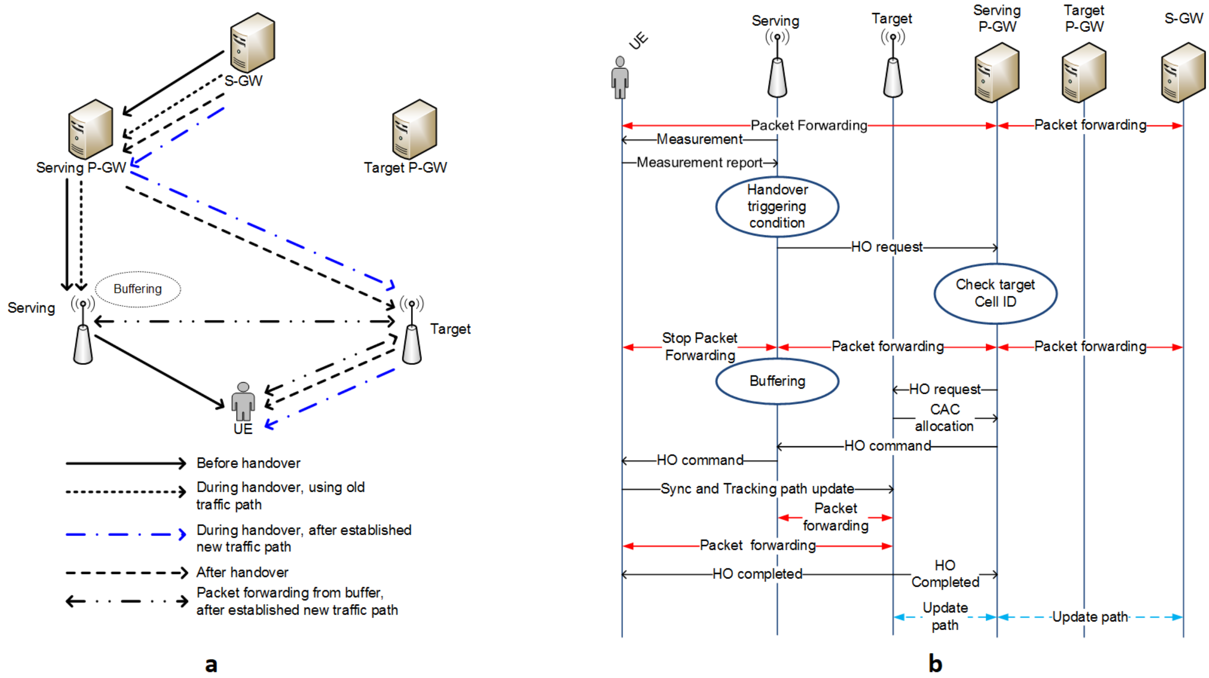

Figure 2. X2 Handover procedures: (a) handover procedures, (b) message flowchart

Figure 2a shows the UE's data traffic paths before handover, during handover with old and new path, after handover and packet forwarding from buffer to the target cell.

Figure 2b shows the messages of handover procedures between UE, serving cell, target cell, serving P-GW and target P-GW. First of all, the serving cell sends a measurement command (measurement) to UE in order to control the connection. UE replies with the measurement report for handover triggering. If handover is necessary, the serving cell sends the handover request (HO request) to the serving P-GW for the check-target-cell-ID process. The serving cell forwards to the target cell a HO request, if the target cell is attached to it (serving and target cells connected to same P-GW); if not, the serving P-GW sends the HO request to the target P-GW, and S1 handover begins.

After the target cell is allocated the radio resource for UE, the serving P-GW replies with the handover command (HO command) to the UE via the serving cell. Also, the serving cell has begun the buffering process. After UE is connected to the target cell, the buffered data is forwarded to UE via the target cell from the serving cell by the X2 interface. The S-GW updates UE's path to the new path.

Inter S1 Handover procedures

Network-based S1 handover is used for seamless mobility when the UE moves to the target eNodeB that is connected to a different P-GW. If handover is necessary, the serving P-GW sends a handover request to the target P-GW (see Figure 3b). Also, the serving cell and serving P-GW begin data buffering for UE.

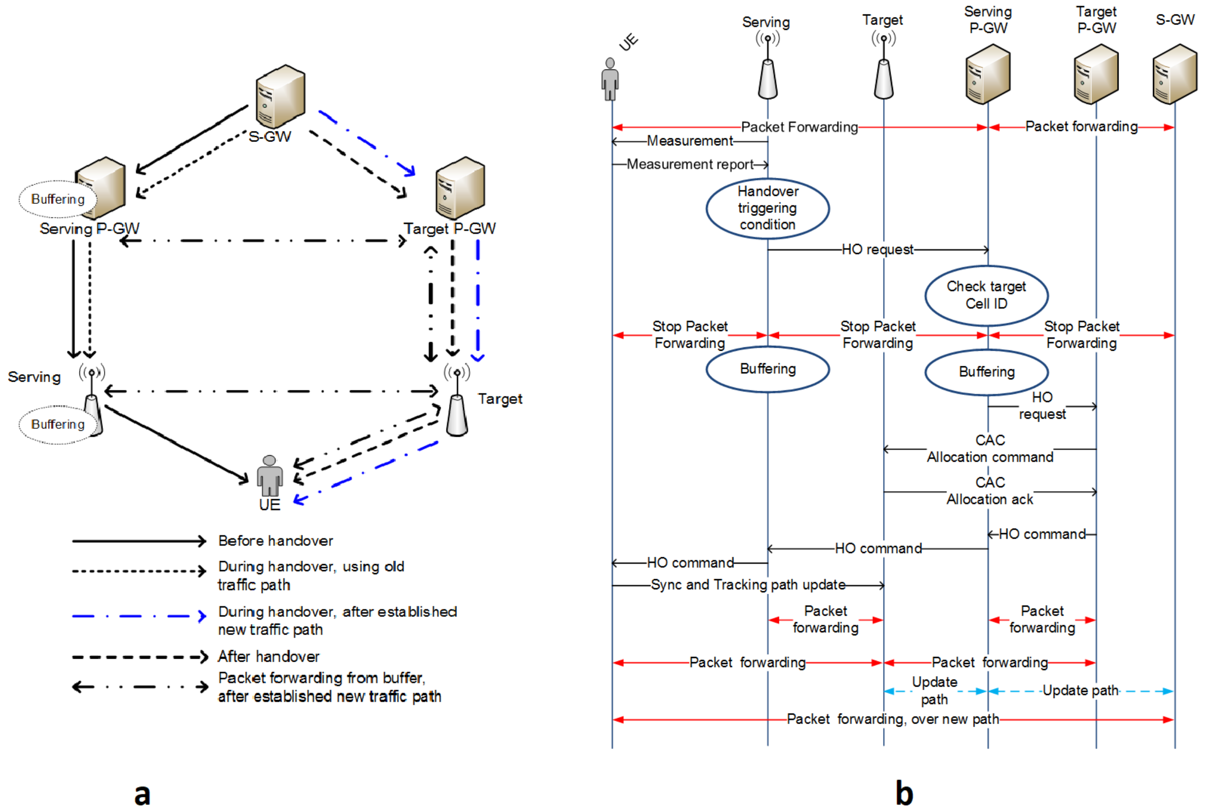

Figure 3. S1 Handover procedures: (a) handover procedures, (b) message flowchart

The target P-GW sends the radio resource allocation request to the target cell. If the target cell is accepted, the target P-GW sends the HO command to UE via serving P-GW and serving cell. After the handover procedure is successful, S-GW updates the data path to the UE. After the UE's connection is established to the target cell, the serving cell forwards the buffered data to UE via the target cell, and the serving P-GW begins data forwarding to UE via target P-GW and target cell.

Moreover, the serving eNodeB releases the radio resource when a 'handover complete' message is received from the target eNodeB. In addition, the target P-GW sends a release message to the serving P-GW. After this message is received, the serving P-GW releases the radio resources and IP address at the serving eNodeB.

Figure 3a shows the two-level data buffering and forwarding processes during S1 handover procedures. At the first level (between serving and target cells), the primary procedure is the

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same as X2 handover: i.e., a serving eNodeB buffers and forwards received packets to the target eNodeB during the handover procedure. Additionally, the serving P-GW stops packet transmission to the serving eNodeB when the handover procedure is started, and stores the packets received from external networks in its buffer. After the handover procedure is successful, the serving P-GW sends all packets (stored in the buffer and newly received from external networks) to the target P-GW.

For example, a UE establishes a connection to a VoIP Server via the serving P-GW and S-GW. As explained previously, the serving P-GW is a mobility anchor for this connection. When the UE moves to the target eNodeB that is connected to a different P-GW, the serving eNodeB sends a handover request to the target eNodeB via the serving and target P-GWs, if handover is necessary. The handover procedure (same as X2 handover) is used between the serving and target eNodeBs. In addition, the serving P-GW sends information about the UE to the target P-GW. This information contains the identifying information of the UE and all established connections with servers. If the handover procedure is successful, the target P-GW sends a request to the SDN controller for updating the routing table and checking/changing the information of the UE (location, tracking ID, IP address, etc.).

The SDN controller updates the routing table to OpenFlow switches for packet transmissions. Then, the packet transmissions of the connections of the UE use a new connection with the target eNodeB and can connect to external networks over the target P-GW. Note that the serving P-GW buffers the packets received from the S-GW and sends them to the target P-GW after the SDN controller completes an update process for the routing table. Additionally, the serving P-GW releases radio resources and the old IP address after the buffering and data forwarding processes are complete.

Simulation Results

This section presents the performance of proposed HoBF that is compared with that of the conventional mobility management of LTE networks in terms of total handover latency and the average values of packet loss in 50 simulation runs.

Simulation Setup

We simulated and verified the proposed HoBF using NS-3.17 with LENA (2017). For the simulation, we created a network topology that consisted of 18 eNodeBs, four P-GWs, and two S-GWs, as shown in Figure 4. Furthermore, the simulation model contained six L2 switches that supported OpenFlow protocol version 1.3 and the Ryu SDN controller. Table 1 lists the parameters used in the simulation; the values are based on LTE release 8 specifications. At the beginning of the simulation, 100 pedestrian users (UEs) with continuous VoIP services are randomly placed in the simulation area, and they are moved according to the random-walk model at speeds of 20 m/s, 40 m/s, 60 m/s, 80 m/s and 100 m/s. All users are registered to a nearby cell that is controlled by the S-GW and is connected to the P-GW. In this section, the Existing Handover (eHO) denotes the existing handover solution that is introduced by the IETF (2016).

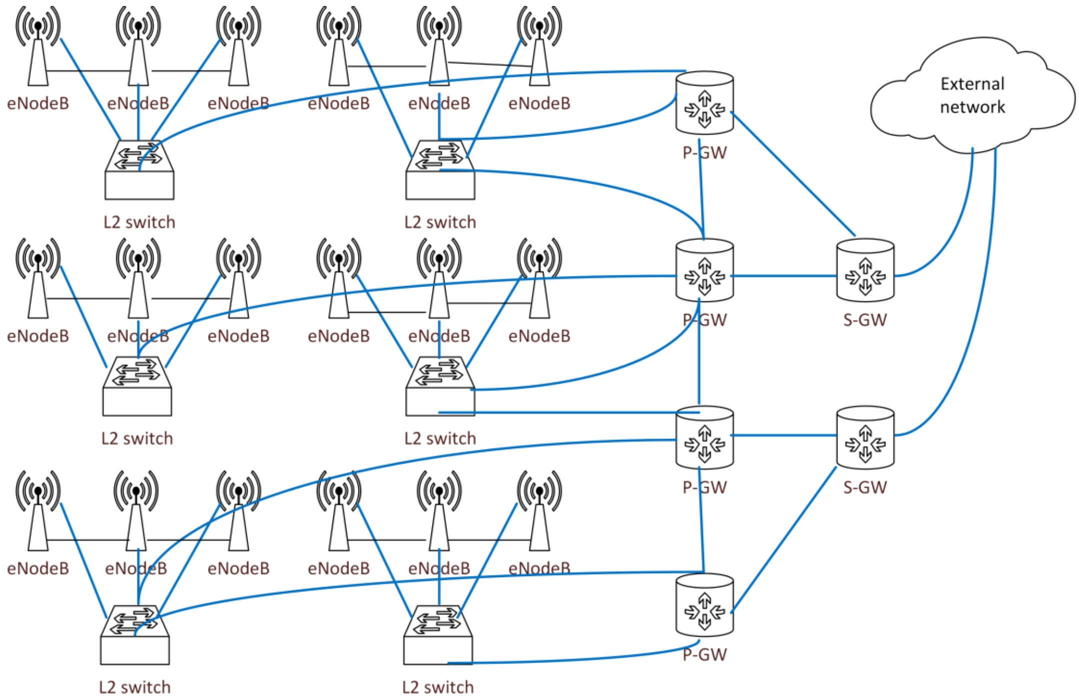

Figure 4. Simulation model with 18 eNodeBs, four P-GWs, two S-GWs

Table 1. Simulation parameters

Parameter	**Value**
Carrier frequency	*2.4 GHz*
Tx power of eNodeBs	*25 dBm, will change if cell radius is changed*
Hysteresis of Event A3	*-72 dBm, will change if cell radius is changed*
Time-to-trigger	*300 ms*
Pathloss model	*128.1+37.5 log10d*
Shadow fading deviation	*2 dB*
Cell radius	*0.5 km, 1 km, 1.5 km, 2 km, 2.5 km, 3 km*
Handover overlap area	*30% of cell radius*

The Handover Latency

Handover latency is the time between last packet received from the serving eNodeB and the time of the first packet received from the target eNodeB. In other words, latency is the execution time of the handover procedure, when UE has disconnected from an old connection and is waiting for a new connection acceptance message from the target eNodeB. In LTE networks, an eNodeB can perform the handover latency, and there is no difference in the definition of handover latency for the handover types.

Table 2. Average Latency of S1 and X2 handovers

Cell Radius	Existing Handover (eHO)		Proposed HoBF	
	S1 handover	X2 handover	S1 handover	X2 handover
0.5 km	*49.3 ms*	*20.7 ms*	*51.8 ms*	*14.18 ms*
1 km	*50.1 ms*	*21.4 ms*	*51.9 ms*	*14.28 ms*
1.5 km	*51.0 ms*	*22.1 ms*	*52.1 ms*	*14.29 ms*
2 km	*52.0 ms*	*23.6 ms*	*52.4 ms*	*14.36 ms*
2.5 km	*53.1 ms*	*23.7 ms*	*52.5 ms*	*14.40 ms*
3 km	*54.2 ms*	*23.8 ms*	*52.6 ms*	*14.41 ms*

Table 2 shows the average values of the handover latency over the given traffic scenario in the eHO and proposed HoBF (50 simulation runs). The X2 handover latency of the proposed HoBF is shorter than that of the eHO. The S1 handover latency of the proposed HoBF is longer than that of the eHO because of the packet forwarding process between P-GWs. Also, the size of cell affects both handover types in the eHO solution. Our proposed HoBF can reduce the effect of cell radius. On the other hand, the little changed latency can support two-level buffering: (1) to queue packets that are stored in the buffer; and (2) to calculate a waiting time of packets at the serving P-GW and eNodeB. The performance and location of the SDN controller are affected (Valtulina 2014) by the change in OpenFlow routing table on L2 switches and routing path calculation processes.

The Packet loss

Packet loss is defined as the packets dropped or lost during the handover procedures (handover execution and completion). Lost packets are retransmitted between users and servers by the new path. The performance of the proposed HoBF and eHO can be compared in terms of average packet-loss ratio. Figure 5 shows the average packet-loss ratio for variation in cell radius. In the X2 handover case for the eHO, packet-loss ratio gradually decreases when cell radius increases. In addition, the figure shows a slight difference between the X2 and S1 handovers of the eHO because the packet buffering and forwarding processes are performed between P-GWs during the S1 handover procedures.

In the case of the proposed HoBF, there is no effect of cell radius because OpenFlow-enabled L2 switches directly forward packets to the target one controlled by the SDN controller. In other words, the packet loss of eHO is increased when the cell radius is increased. It is a deficiency of eHO in future networks that are heterogeneous and complex. Note that the buffer size of the switches is sufficient for forwarding a large number of packets.

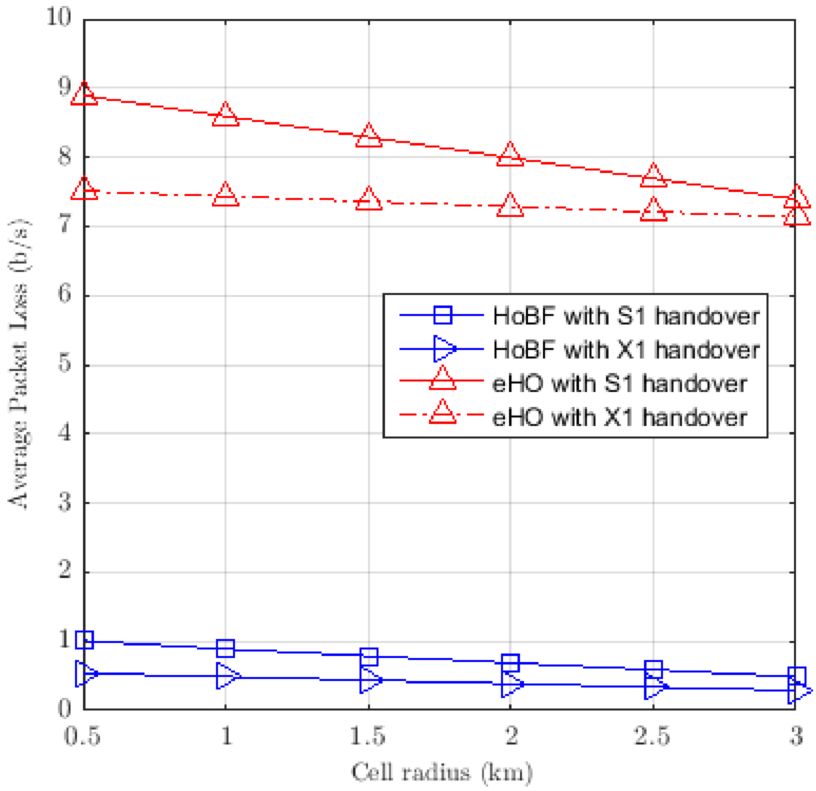

Figure 5. The effect of cell radius on the average packet loss

The Handover Failures

The measure of Handover Failures is defined as the ratio of the sum of dropped handovers, radio link failures (during handover procedures), and ping-pong handovers to the total number of handovers. The total number of handovers is the sum of all handovers that are triggered to the target cell. Figure 6 shows the ratio of handover failures for a number of handover scenarios. In the low-speed case, the proposed HoBF produces a failure ratio of 0.05%, compared with that of the eHO at 0.12%. Also, no Radio Link Failures (RLFs) and dropped handovers are observed, because many handovers are finished before RLF occurs and mobility anchors reduce the number of dropped handovers.

In the high-speed case, the difference between the eHO and HoBF is less visible. Here, the number of RLFs is affected because two-level buffering of messages is added to the handover procedures and affects the handover execution time.

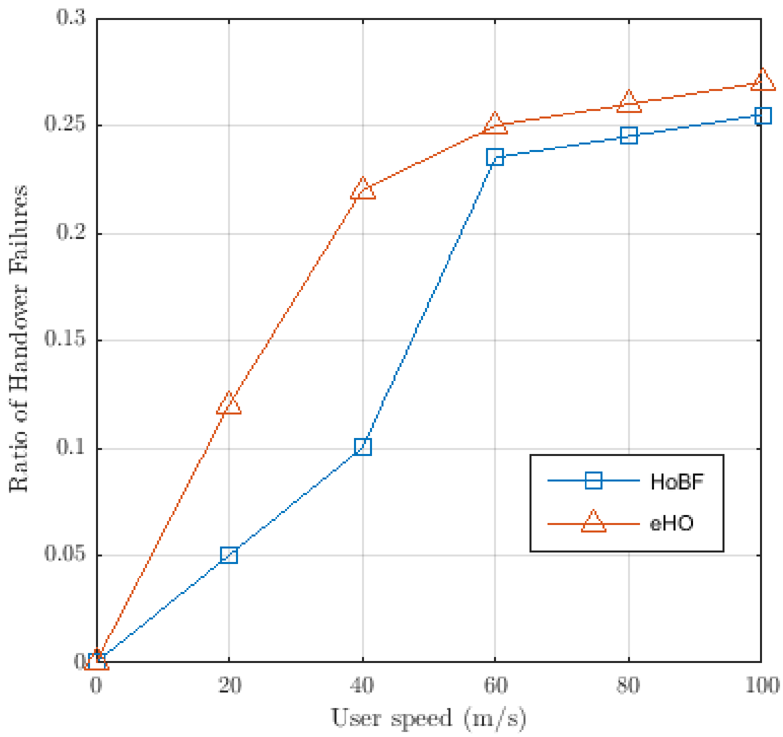

Figure 6. The impact of UE's speed on handover failure probability

Conclusion

This paper presents handover management for an SDN-based DMM solution in LTE networks. P-GWs are distributed close to the LTE radio access network to handle the mobility of users. Our proposal changes the handover procedures and defines two-level buffering in a DMM solution. The two levels of buffering in support of the handover procedure between different P-GWs are introduced in order to reduce the packet loss. We performed a simulation to compare the proposed HoBF with the eHO. From our simulation results, the advantages of our solution are the reduced values of X2 handover latency and packet loss when users are moving between eNodeBs or different P-GWs. Also, our proposed solution can reduce the effect of cell radius and improve the management of handover between the small cells and macrocells. Future work will focus on the implementation our solution for heterogeneous and complex networks.

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References

IETF. 2016. 'A distributed mobility management (DMM)'. Available from https://datatracker.ietf.org/wg/dmm/about/ .

Ameigeiras, P. 2015. 'Link-level access cloud architecture design based on SDN for 5G networks'. *IEEE Network*, Volume 29, Issue 2, pp. 24-31.

LENA documentation. 2017. 'LENA v8 documentation'. Available from: http://lenaold.cttc.es/manual/lte-design.html, retrieved January 2017.

Ernest, P P. 2013. 'Network-based distributed mobility management: Design and analysis'. *IEEE 9th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*. Lyon, France.

Open Networking Foundation. 2012. 'OpenFlow Switch Specification version 1.3'. Available from: http://www.opennetworking.org .

Giust, Fabio; Bernardos, Carlos J.; de la Oliva, Antonio. 2014. 'Analytic evaluation and experimental validation of a network-based IPv6 distributed mobility management solution'. *IEEE Transactions on Mobile Computing*, Volume 13, Issue 11, pp. 2484-2497.

Giust, Fabio; Cominardi, Luca; Bernardos, Carlos J. 2015. 'Distributed mobility management for future 5G networks: overview and analysis of existing approaches'. *IEEE Communications Magazine*, Volume 53, Issue 1, pp. 142-149.

Costa-Requena, Jose, et al. 2015. 'SDN and NFV integration in generalized mobile network architecture'. *IEEE European Conference on Networks and Communications (EuCNC)*. Paris, France.

Ko, H I. 2017. 'SDN-based distributed mobility management for 5G'. *2017 IEEE International Conference on Consumer Electronics (ICCE)*. Las Vegas, USA.

Kuang, Q, et al. 2015. 'A measurement-based study of handover improvement through range expansion and interference coordination'. *Wireless Communications and Mobile Computing*, Volume 15, Issue 14, pp. 1784-1798.

Kukliński, Slawomir; Li, Yuhong; Dinh, Khoa Truong. 2014. 'Handover management in SDN-based mobile networks'. *IEEE Globecom Workshops (GC Wkshps)*. Austin, Texas, USA.

Lee, Jong-Hyouk; Bonnin, Jean-Marie; Lagrange, Xavier. 2012. 'Host-based distributed mobility management support protocol for IPv6 mobile networks'. *IEEE 8th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*. Barcelona, Spain.

Lee, Jong-Hyouk; Bonnin, Jean-Marie; You, Ilsun. 2013. 'Comparative handover performance analysis of IPv6 mobility management protocols'. *IEEE Transactions on Industrial Electronics*, Volume 60, Issue 3, pp. 1077-1088.

Cisco. 2017. 'Global mobile data traffic forecast update 2015-2020'. *Cisco Visual Network Index White Paper*. Available from: https://www.cisco.com/c/en/us/solutions/collateral /service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.html .

Nguyen, Tien-Thinh; Bonnet, Christian. 2013. 'DMM-based inter-domain mobility support for proxy mobile IPv6'. *IEEE Wireless Communications and Networking Conference (WCNC)*. Shanghai, China.

Nguyen, Tien-Thinh; Bonnet, Christian. 2015. 'A hybrid centralized-Distributed Mobility Management for supporting highly mobile users'. *IEEE International Conference on Communications (ICC)*. London, UK.

Nguyen, Tien-Thinh; Bonnet, Christian; Harri, Jérôme. 2016. 'SDN-based distributed mobility management for 5G networks'. *IEEE Wireless Communications and Networking Conference (WCNC)*. Doha, Qatar.

Perkins, C; Johnson, D; Arkko, J. 2011. 'Mobility support in IPv6'. Internet Engineering Task Force, RFC 6275. Available from: https://tools.ietf.org/html/rfc6275 .

Sanchez, M. Isabel; de la Oliva, Antonio; Mancuso, Vincenzo. 2016. 'Experimental evaluation of an SDN-based distributed mobility management solution'. *ACM Proceedings of the Workshop on Mobility in the Evolving Internet Architecture*. New York, USA.

Valtulina, Luca; Karimzadeh, Morteza; Karagiannis, Georgios. 2014. 'Performance evaluation of a SDN/OpenFlow-based Distributed Mobility Management (DMM) approach in virtualized LTE systems'. *IEEE Globecom Workshops (GC Wkshps)*. Austin, Texas, USA.

Wang, Lili, et al. 2014. 'Survey on distributed mobility management schemes for Proxy mobile IPv6'. *2014 IEEE 11th Consumer Communications and Networking Conference (CCNC)*. Las Vegas, USA.

Yang, Hyunsik; Kim Youngham. 2016. 'SDN-based distributed mobility management'. *2016 International Conference on Information Networking (ICOIN)*. Kota Kinabalu, Malaysia.

Kyung, Yeunwoong, et al. 2015. 'Software defined service migration through legacy service integration into 4G networks and future evolutions'. *IEEE Communications Magazine*, Volume 53, Issue 9, pp. 108-114.

A Trust-based Defence Scheme for Mitigating Blackhole and Selective Forwarding Attacks in the RPL Routing Protocol

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Abstract: The routing protocol for low-power and lossy networks (RPL) has gained prominence as the standard IoT routing protocol. However, it faces like many other routing protocols diverse attacks. Many studies have been proposed to secure the RPL protocol, and simulation studies have been put forward as the main research method, while testbed experiments, though an authentic research and testing method, have been ignored. Although testbed experiments and simulation studies have their strengths and limitations, testbed techniques could be used as a verifiable validation method for simulation studies. This study is a follow up research work to validate our simulation study, which addressed Blackhole attacks in the RPL routing protocol. In addition, Selective Forwarding attacks are also addressed. It implements a testbed while embedding our Trust-based RPL protocol and the standard RPL protocol in a smart environment configuration. Based on the test experiments, we provide a proof-of-concept of the validity of our claim that our Trust-based RPL protocol provides a comprehensive defence (simulation and testbed) against Blackhole and Selective Forwarding attacks.

Keywords: Trust, RPL, Blackhole attack, Selective Forwarding attack, AS-XM1000

Introduction

The Internet of Things (IoT) — the connectivity, communication and management of vast numbers of networked devices (machines and sensors) by means of the Internet — is a pervasive phenomenon that is creating a global technological disruption. From the production plant to the intensive care unit of a hospital to a smart home, IoT is rapidly making its presence felt. As the proliferation of these devices permeate our society, the progressive reliance on these intelligent, interconnected devices in our everyday life increases. This fact, coupled with the rising challenge of cyber threats and security attacks raises the question: how do we ensure that this massive number of online devices are protected from interference and malicious attacks that could compromise their security and hence create public safety concerns, which, in turn, could hinder the potential growth and benefits of this new technology wave?

Undoubtedly, for the safe and reliable operation of connected IoT devices the issue of security of these devices is paramount. However, identifying the ideal systemic security approach to adopt in order to have a secure and robust IoT ecosystem is not an easy task. Although enterprise networks, firewalls and protocol systems can manage a high level of Internet traffic, a study (Pongle, 2015b) shows, however, that the protection of resource-constrained and deeply embedded terminal sensor devices having specific functionalities is a challenge.

RPL (Routing Protocol for Low power and lossy networks) is considered the standard IoT routing protocol (Gaddour, 2015). An important characteristic of RPL is its design for a network of resource-constrained devices with lossy links and high Packet Error Rate (PER). The growing acceptance of RPL is due to its adaptability to diverse network topologies and its Quality of Service (QoS) features, amongst others. However, secure operation mode is not enabled in RPL, and this makes RPL vulnerable to various routing attacks. This has been reported in Djedjig, Tandjaoui, & Medjek (2015); Gaddour *et al.* (2015); Glissa, Rachedi, & Meddeb (2016) and in our work (Airehrour, Gutierrez, & Ray, 2016b).

In our work (Airehrour, 2016b), we proposed a Trust-based secure RPL routing protocol against Blackhole attacks. Subsequently, we improved this work to address Selective Forwarding attacks (Airehrour, Gutierrez, & Ray, 2017). In both studies, simulation results proved our secure Trust-based system for RPL protocol to be a promising solution to protect RPL from routing attacks. To take this further, this study, proposes a testbed experiment to investigate the authenticity of our simulation claims with respect to the work presented in Airehrour (2016b). In our testbed, we have embedded our Trust-based system in RPL protocol, deployed it and tested our secure protocol against the standard RPL implementation.

The remainder of the paper is organized as follows. The Related Work section discusses RPL protocol operations, related studies, and the need for testbed experiments to validate simulation studies in secure RPL protocols. In the Trust and Reputation Based RPL Objective Function section, our previous study (Airehrour, 2016b) on Trust-based RPL protocol and the validation process is discussed. The testbed setup and demonstration is shown in the Testbed Experiments section, which shows the efficacy of our proposed Trust-based system and its consistency with the simulations performed in Airehrour (2016b). We conclude with some thoughts in the Conclusion and Future Work section.

Related Work

Routing in RPL

RPL forms a tree-like topology with a root node at the top (commonly referred to as the sink node) and leaves at the edges (known as sender nodes). RPL, however, is not restricted to a tree topology because it can cope with redundant links that are required in Low-power and Lossy Networks (LLNs) (Winter, 2012). In RPL, the movement of traffic is described in terms of the "up" and "down" directions. Traffic moving from the sender nodes to the sink node is referred to as the “upward” traffic, while traffic moving from the sink node to the sender nodes is regarded as the “downward” traffic. During a RPL operation, links are required to be bidirectional to create both upward and downward routes to and from any node. For a node to be considered a parent, its reachability must be ascertained using an external mechanism that is being activated during the parent-node selection process. This is to ensure the link properties and neighbour reachability are defined.

RPL is considered a distance vector protocol, which performs routing either in a downward or upward fashion. All information regarding the topology of RPL is maintained as a graph called the Destination Oriented Directed Acyclic Graph (DODAG). The DODAG consists of paths from the sender nodes to the sink node. During routing, every node maintains its Rank relative to its position in the DODAG tree. A node’s Rank is a calculated 16-bit monotonic scalar value that is used for loop avoidance, and this value is calculated according to the specified Objective Function (OF).

Every DODAG is populated with parent information. The parent data is control and route information, which is used for routing and RPL network stability. The packets used by DODAG are: DODAG Information Object (DIO), Destination Advertisement Object (DAO), and DODAG Information Solicitation (DIS) for transmitting the DODAG information. A DODAG formation is administered using the following guidelines: Path metrics, OF, Rank of a node for loop avoidance in the DODAG tree, and any stipulated policies of a node (Winter, 2012). Figure 1 shows an illustration of the route-build process in RPL. From time to time, a node periodically re-evaluates the Rank of its parent to maintain a loop-free route topology.

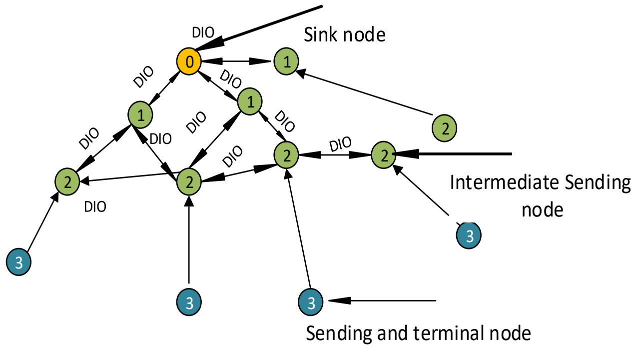

Figure 1. A RPL instance displaying DIO broadcast.

Routing Metrics and Objective Function in RPL

According to the IETF specification (Winter, 2012), different OFs could be specified for RPL. Traffic in a RPL network is transported and delivered based on the defined OF, which could be different for various traffic types. OFs are defined to optimize some particular metrics while also fulfilling specific constraint(s). Accordingly, the OF is used for effective routing path definition based on specific requirements. These requirements could be embedded in a series of programming logic in IoT motes and utilized by RPL for routing purposes. A fundamental reason for the adoption of RPL for LLNs is the separation of the OF from the central protocol specification (Winter, 2012), thus making it easy for different OF specifications to be built into RPL and which, in turn, makes it useful for a wide range of application scenarios.

Routing metrics are scalar values for determining the 'cost' of a route path. The values are used for making optimal routing decisions, especially when multiple routes are identified. A formal specification of how routes are defined, selected and optimized is regarded as the objective function (OF) of the RPL routing protocol. The network of resource-constrained sensor devices uses metrics defined in the OF to make optimal routing decisions. The use of a scalar value for route determination makes it particularly attractive for embedding trust as a metric for route computation, and the isolation of malicious nodes. Routing metrics are important to the successful creation and preservation of any network topology. Traditional networks employ the use of static metrics (hop count, bandwidth) for routing decisions. The IETF RFC 6550 specification of RPL (Winter, 2012) does not define specific forwarding metric policies. Furthermore, in the RPL draft from the IETF, constraints are also specified, which are used as filters for the specification of what should be included or excluded in the routing metric dynamics of RPL. Various literatures have discussed the RPL routing protocol and have proposed different metrics for LLNs, which have been presented in Djedjig *et al.* (2015), Gaddour *et al.* (2015) and Glissa *et al.* (2016).

Security Vulnerabilities in RPL

Studies have been undertaken that bring to the fore the vulnerabilities in the RPL routing protocol. The authors in Pongle & Chavan (2015b) conducted a study on possible attacks that could be perpetrated against RPL. Similar studies have been conducted and are reported in Airehrour, Gutierrez & Ray (2016a) and Nawir, Amir, Yaakob & Lynn (2016), while the impact of attacks on the RPL protocol has been reported in Kumar, Matam & Shukla (2016). In RPL protocol, a Blackhole attacking node advertises itself by broadcasting a false and low DIO rank value to the sink node. This causes nodes within its reach to select it as their parent for a downward route transmission from the sink node. The Blackhole node immediately commences the discard of packets upon receipt from its neighbour nodes. Table 1 provides a summary of recent literature addressing RPL protocol attacks. The table provides the attacks addressed, attack detection strategy, and the method of validation. In nearly all the cases provided, simulation was used as the method of verification. This brings to bear, therefore, the need for a realistic live study, such as testbed experiments, that will validate the claims presented in the literature addressing the RPL protocol attacks.

In addition, a Selective Forwarding attacking node selectively or randomly forwards packets it has received. The aim of this type of attack is two-fold. The first is the desire to degrade network performance by increasing the packet loss rate. The second is to act as a 'man in the middle' in order to inhibit other nodes that are seeking to communicate through it (the attacker) with the sink node. This scenario creates a denial of service (DoS).

Table 1. A summary of RPL protocol research improvements and validation methods

Reference	Attack(s) Isolated	Attack Detection Strategy	Validation Method
Real Time Intrusion and Wormhole Attack Detection in Internet of Things (Pongle & Chavan, 2015a)	Wormhole attacks	Anomaly-based detection system	Simulation
A Specification-Based IDS for Detecting Attacks on RPL-Based Network Topology (Le, Loo, Chai, & Aiash, 2016)	RPL topology attacks	Specification based detection system	Simulation
Ultra-Lightweight Deep Packet Anomaly Detection for Internet of Things Devices (Summerville, Zach, & Chen, 2015)	General purpose IDS system	n-gram bit-pattern matching	Empirical
Enhancing RPL for Robust and Efficient Routing in Challenging Environments (Kantert *et al.*, 2015)	Sinkhole	Trust-based method	Simulation
A Distributed Monitoring Strategy for Detecting Version Number Attacks in RPL-Based Networks (Mayzaud, Badonnel, & Chrisment, 2017)	Version Number attacks	Distributed Monitoring Strategy	Simulation
A secure routing protocol based on RPL for Internet of Things (Glissa *et al.*, 2016)	Rank attacks	Hash chain authentication	Simulation

Reference	Attack(s) Isolated	Attack Detection Strategy	Validation Method
Trust-based RPL for the Internet of Things (Djedjig *et al.*, 2015)	Rank attacks	Trust-based	Simulation
Strong Authentication Countermeasures Using Dynamic Keying for Sinkhole and Distance Spoofing Attacks in Smart Grid Networks (Taylor & Johnson, 2015)	Sinkhole and Distance Spoofing Attacks	Dynamic key Authentication	Simulation
Enhancing RPL Resilience Against Routing Layer Insider Attacks (Heurtefeux, Erdene-Ochir, Mohsin, & Menouar, 2015)	Selective Forwarding attacks	Duplication of packets for redundancy	Simulation
Addressing DODAG Inconsistency Attacks in RPL Networks (Sehgal, Mayzaud, Badonnel, Chrisment, & Schönwälder, 2014)	DODAG Inconsistencies		Simulation
Denial-of-service detection in 6LoWPAN based Internet of Things (Kasinathan, Pastrone, Spirito, & Vinkovits, 2013)	DoS attacks	Signature-based detection	Empirical

Validating Simulation via Testbed

Simulation has over the years proved to be a fundamental testing and diagnostic tool. This is especially true for network simulations, and this has become a global standard for wireless sensor network testing and evaluation. However, as sophisticated as a simulation may be, it is often inadequate as an investigation platform for real-world deployments (Fortier, 2002; Tan, 2010). Sensors, and indeed IoT sensors, have continued to improve in technological advancements; their form factors have become, and are continuing to be, smaller by the day while their processing capabilities have soared in recent times. In addition, some of the measuring devices on these sensors have not been adequately and accurately simulated (Fortier, 2002).

A testbed, on the other hand, is a collection of deployed hardware infrastructure, developed for physical network experimentation and integrated with software services, for controlling and managing hardware and experiments executed on it. Therefore, a physical testbed becomes imperative, as it is designed to support physical experimentation, which addresses the gaps that simulations are not able to fill. A fundamental feature of a testbed is its focus on a specific aspect of the total system. This helps in furthering a deeper understanding of the functional and operational requirements of the system while capturing specific behaviours under unique conditions, which otherwise would not have been captured during a simulation. Results gathered during testbed runs can be quantitatively measured and analysed, on which design decisions can be predicated from the theoretical and empirical findings.

Trust and Reputation Based on RPL Objective Function

RPL uses routing metrics defined in its Objective Function to create the DODAG. Essentially, the routing metrics help in the creation of the network routes and hence result in optimal routes. The Contiki platform (Thingsquare, 2016) uses Minimum Rank with Hysteresis Objective Function (MRHOF) by default, which minimizes the expected transmission count (ETX) values.

This study compares the MRHOF implementation of RPL and our Trust-based implementation of RPL. Our previous work (Airehrour, 2016b) was compared with a MRHOF implementation of RPL and, based on that, testbed experiments were similarly conducted.

In our previous work (Airehrour, 2016b), a Trust-based system was proposed for RPL protocol, which provides security against Blackhole attacks. The Trust-based protocol provides a feedback-aware trust system for a RPL network. In this system, a node evaluates the trust value of its neighbour-node with respect to the good forwarding behaviour of the node. This study was further improved for the detection and isolation of Selective Forwarding attacks, and this was reported in Airehrour *et al.* (2017). We recap some fundamental trust computations in our previous study below.

Computing and Embedding Trust in RPL

Algorithm for the detection of Blackhole

```
Let N1 ← one unfilled node in the NeighborNodeList [ ]
Let N2 ← another node next to N1 in the NeighborNodeList [ ]
```

Compute $EP_{ij} = \frac{N_{dlv}}{N_{sent}}$

```
    If (N1.ETX<= ETX_Limit) & (N2.ETX<=ETX_Limit)
    If (N1.Rank <= Rank_Self) & (N2.RANK <= RANK_Self)
       Preferred_Parent = N1.EP > N2.EP ? N1 : N2;
    Else
          If (N1.Rank <= Self_Rank) || (N2.Rank <= Self_Rank)
             Preferred_Parent = N1.Rank < N2.Rank ? N1: N2
          Else
             Preferred_Parent = NULL;
  Else
       If (N1.ETX <= ETX_Limit) || (N2.ETX <= ETX_Limit)
          Preferred_Parent = N1.ETX <= N2.ETX ? N1 : N2;
       Else
           Preferred_Parent = NULL;
  Return Preferred_Parent
End program.
```

Figure 2. Trust algorithm for trusted parent selection and isolation of Blackhole and Selective Forwarding nodes (Airehrour et al., 2016b).

The trusted node(s) are selected for routing decisions while maintaining the rank order of all nodes in the RPL network. Trust is computed based on Equation 1. while Figure 2 presents the algorithm for trusted parent selection and isolation of blackhole nodes.

$$EP_{ij} = \frac{N_{dlv}}{N_{sent}} \quad (1)$$

In Equation 1, N_{dlv} is the number of node i's packets delivered through node j, and N_{sent} is the total number of packets sent by node i to node j.

Blackhole and Selective Forwarding Detection and Isolation

This section describes the detection and isolation of Blackhole and Selective-Forwarding nodes. After the computation of the trust values of nodes, the nodes are ranked in the magnitude of their trust values while maintaining the rank order of nodes, as specified in RFC 6550 (Winter, 2012). The nodes with high trust values are used for secure routing decisions. To achieve the objective above, we assumed that the network operates in promiscuous mode and hence we modified the RPL protocol to achieve the functions stated below:

- Every child node keeps a record of the number of packets forwarded to its parent.
- A child-node assesses the number of packets forwarded by a parent-node on its behalf. This is much like the DAO and DAO-ACK in RPL.
- A node queues up its packets in its buffer for delivery. In coding the Blackhole behaviour, an attacking Blackhole node always keeps its buffer empty, since it discards packets sent to it and does not report packets forwarded to its child node, whereas a normal node reports its details to its child node.

Testbed Experiments

The testbed experiment undertaken in this study serves as a proxy for a smart home environment, which is vulnerable to attacks. In the testbed setup, fourteen AS-XM1000 motes (refer to Figure 3) based on the Telos-B system were deployed in a research laboratory (fourth floor, School of Engineering, Computer and Mathematical Sciences) at the Auckland University of Technology's City campus. The coverage area was approximately 30 metres by 30 metres. The InstantContiki 3.0 platform (Thingsquare, 2016) was used to carry out the experiment. Three mote types were deployed: one UDP sink mote; twelve UDP sender motes; and two Blackhole attacking motes. Although the sender and attacking motes deployed were stationary, they could still communicate with the UDP sink, since all of them were under the coverage area of the UDP sink mote. The sink mote was connected to a desktop PC running the Contiki/Cooja emulation program, while the sender and Blackhole motes were evenly distributed across the testbed location.

Figure 3. AS-XM1000 mote

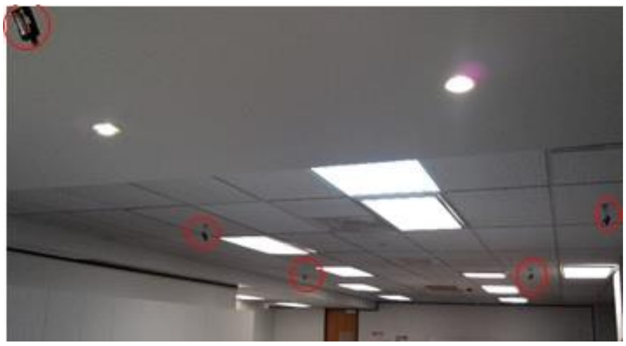

Figure 4. Physical deployment of 14 XM1000 motes in the research lab

Table 2 lists the deployment settings and configurations. To complete the testbed setup, the respective UDP_sink, UDP_sender and malicious codes were embedded into the XM1000 motes using ContikiRPL (MRHOF) and Trust-based RPL. Figure 4 shows a physical partial view of the motes deployment in the research laboratory. The motes are circled in red. In the accompanying sections, the testbed performance results between MRHOF-RPL and the proposed Trust-based RPL under Blackhole attacks are discussed. In the figures 5 and 6 the motes are depicted as y.y. Hence, mote 1 is shown as 1.1; mote 2 as 2.2. In addition, the child-parent relationship is indicated with a blue arrow along with the expected transmission count (ETX) value between them.

Table 2. Testbed Parameters

Testbed tool	Contiki/Cooja 3.0
Testbed coverage area	30m x 30m
Total number of XM1000 motes	14
Blackhole motes	2 (Motes 13 and 14)
Mote deployment environment	Smart building
RX Ratio	30-100%
TX Ratio	100%
TX Range	50m
Interference Range	55m
Routing Protocols	MRHOF-RPL and Trust-based RPL
Network protocol	IP based

Isolation of Blackhole Attacks

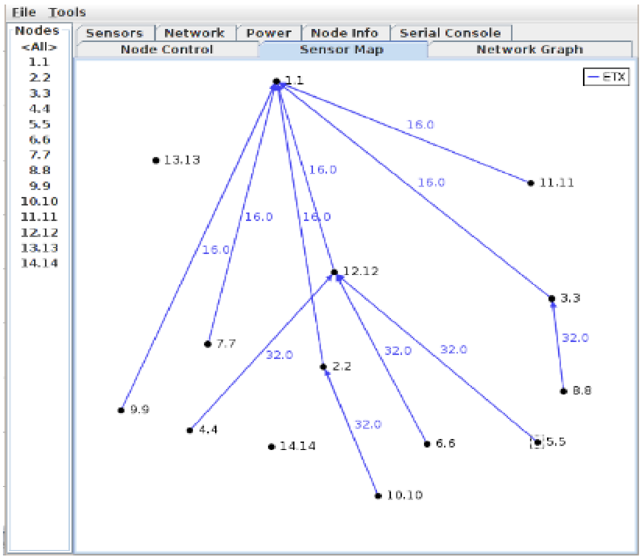

Figure 5. Blackhole mote isolation using Trust-based RPL protocol

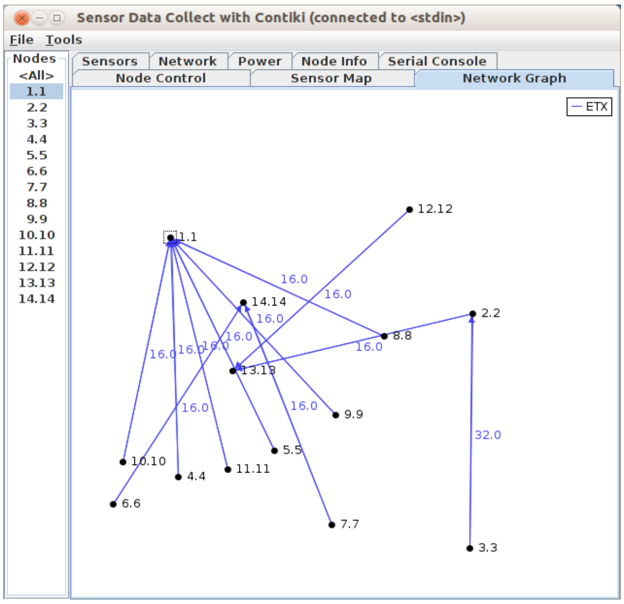

Figure 6 MRHOF-RPL route topology segmentation under Blackhole attacks during the testbed experiment with XM1000 motes

Figures 5 and 6 show snapshot captures of the testbed network topology formation of XM1000 motes under the Trust-based RPL and MRHOF-RPL protocols during Blackhole attacks. The Trust-based RPL could detect and isolate motes 13 and 14 from its route topology formation due to their malicious behaviour in the network. As observed from Figure 5, motes 13 and 14 were not considered for routing decisions in the network. However, the MRHOF-RPL protocol standard (Figure 6) could not mitigate the effect of the Blackhole activities of motes 13 and 14, respectively. Consequently, three disjointed network segments were formed, which resulted in unsuspecting motes 2, 3 and 12 selecting mote 13 as their parent, and motes 6 and 7 selecting mote 14 as their parent. The remaining motes were connected to the sink mote. Furthermore, as evident in Figure 7, the Trust-based RPL could detect and isolate Blackhole attacks during routing operations. The first five minutes of RPL operation witnessed the detection of a slightly higher level of initial Blackhole attacks among the malicious motes. Our Trust-based RPL could identify and isolate the Blackhole attack motes and thus the malicious motes were not considered for routing decisions in the network. The testbed result discussed above agrees with the simulation study presented in our paper (Airehrour, 2016b). In both cases, the testbed and simulation studies had similar detection pattern and detection rate of Blackhole attacks during RPL operation.

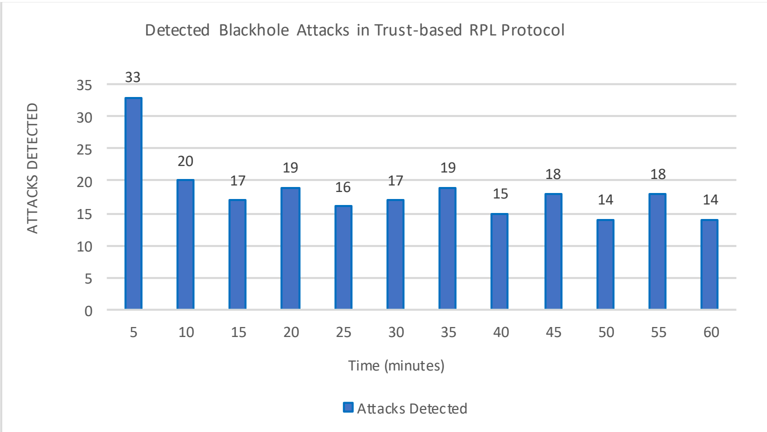

Figure 7. Blackhole attacks detection and isolation during the testbed experiment

Moreover, as MRHOF-RPL protocol was unable to detect any of the Blackhole attacks in the network, the protocol experienced a high frequency of mote Rank changes as a result of an incessant re-alignment of a child mote with new parent mote (see Figure 8). This destabilized the network topology and hence made the network inefficient. In addition, as evident from the results presented in Figure 8, the Trust-based RPL protocol maintained the number of its mote Rank changes within 15 – 55, while MRHOF-RPL had a range between 16 – 246 mote Rank changes. Also, it can be observed that MRHOF-RPL had a significant number of mote Rank changes compared to the Trust-based RPL protocol. This indicates that the activities of the Blackhole attack motes during RPL's operation had a significant impact on MRHOF-RPL protocol during the testbed experiments.

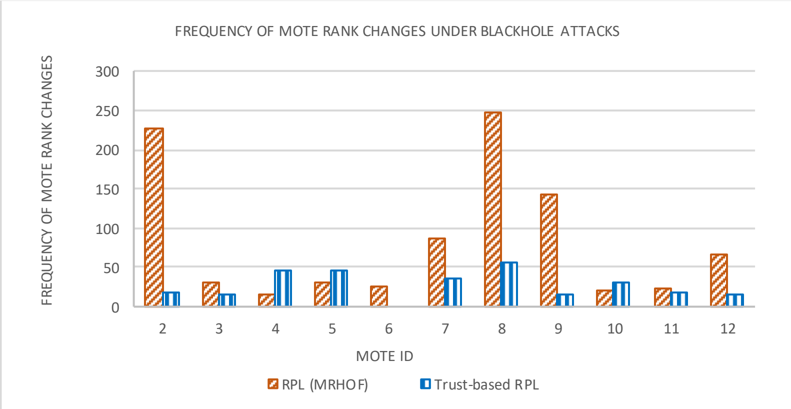

Figure 8. Comparison of frequency of mote Rank changes under Blackhole attacks during the testbed experiment

Network Performance Evaluation

In this section, we present the testbed analysis of the network throughput and the packet loss rates of MRHOF-RPL and our Trust-based RPL protocols while under Blackhole attacks. The network throughput (kilobits per second), which is the amount of data transmitted in each period over a given communications channel, is presented. A higher throughput shows a more stable network topology despite the presence of Blackhole attackers. As shown from the throughput comparison presented in Figure 9, the Trust-based RPL protocol maintained a significantly higher throughput measurement over and above MRHOF-RPL. Motes 7 and 8 achieved the highest and lowest throughputs of 3 kbps and 0.34 kbps under MRHOF RPL. Under the Trust-based RPL, motes 5 and 4 achieved the highest and lowest throughputs of 6.6 kbps and 2 kbps, respectively. This clearly implies that our Trust-based RPL protocol delivers better network performance than the MRHOF-RPL under Blackhole attacks. The testbed network throughput measurements reported here are similar to the simulation results reported by our simulation study in Airehrour *et al.* (2016b).

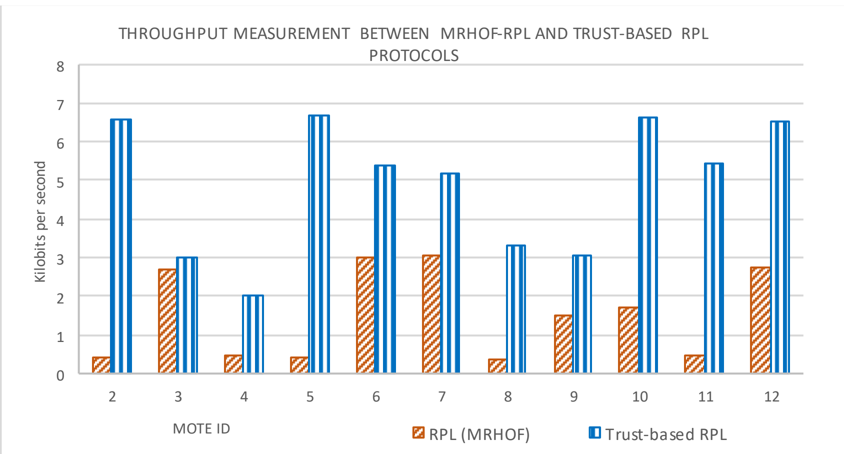

Figure 9. A throughput performance measurement between MRHOF-RPL and Trust-based RPL protocols

Figure 10 compares the packet-loss percentage between the Trust-based RPL and MRHOF-RPL. Packet percentage loss is the ratio of the total packets lost to the total packets sent between a sender and a sink mote. A lower loss rate is indicative of better packet delivery and hence a more stable link between network nodes. From Figure 10, the Trust-based RPL protocol maintained a packet loss rate of less than 28%, but MRHOF-RPL had 60 to 75% packet loss rates. The testbed packet-loss-rate results presented in Figure 10 agree with the simulation study results reported in Airehrour *et al.* (2016b).

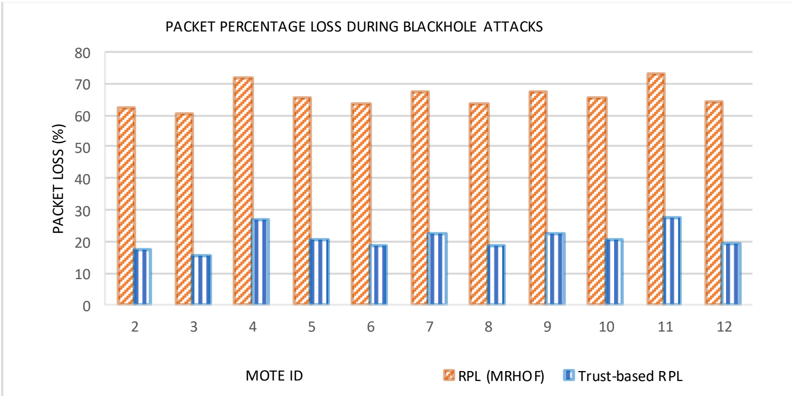

Figure 10. Percentage of packet loss comparison between Trust-based RPL and MRHOF-RPL under Blackhole attacks during the testbed experiment

Isolation of Selective Attacks

The testbed experiment was extended to test the performance of the Trust-based RPL protocol and MRHOF-RPL under Selective Forwarding attacks using the deployed XM1000 motes. When the test was conducted, an instance of the network topology was captured in the sensor data collection menu of Contiki/Cooja, and the topology instance is displayed in Figure 11. It reveals that the Trust-based RPL protocol could detect and isolate malicious motes 13 and 14 from its route topology formation. However, in Figure 12, which is the network topology formation of MRHOF-RPL, it could not mitigate the effect of malicious activities of the Selective Forwarding attacking motes (13 and 14) in the network. Motes 3, 6 and 8 were drawn to malicious mote 13 while motes 2, 7 and 12 were drawn to malicious mote 14. The rest of the motes, however, were connected to the sink mote. Figure 12 illustrates the situation whereby packets sent to mote 1 by motes 2, 7 and 12 cannot be delivered during the period they were connected to mote 13. Also, packets sent by motes 2, 7 and 12 cannot be received by mote 1 during the time they were connected to malicious mote 14, since the network is segmented and cannot connect to the central sink mote.

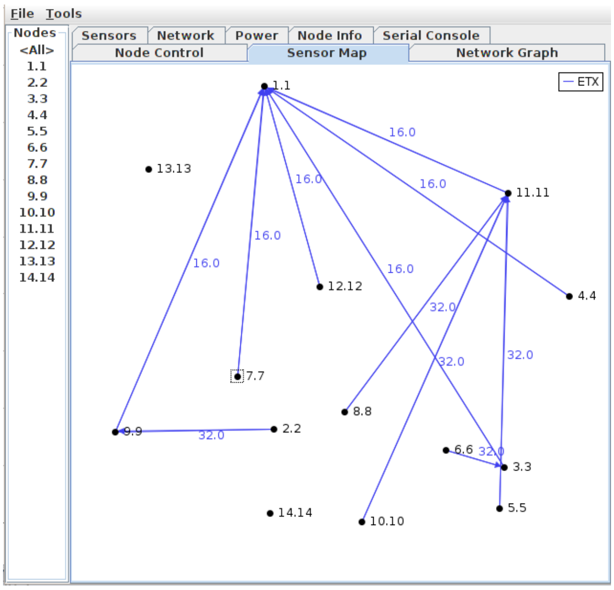

Figure 11. Isolation of Selective Forwarding attacks using the Trust-based RPL protocol

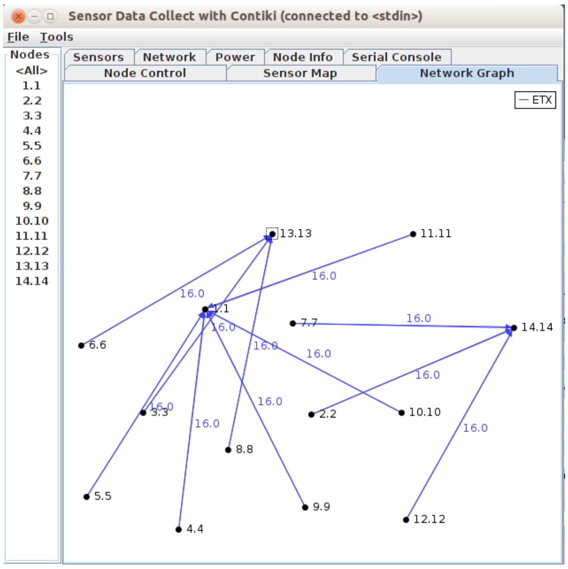

Figure 12. Route topology segmentation by Selective Forwarding attacking nodes under MRHOF-RPL

Detection and Isolation of Attack Nodes

The testbed experiment in Figure 13 shows the detection of attacks perpetrated by malicious motes 13 and 14 performing Selective Forwarding attacks. The first five minutes shows the detection of a high amount of attacks, while the remaining simulation period (10 – 60 minutes) shows a relatively stable number of attacks detected (50 – 75). The initial high flow of attacks and detection in the first five minutes is attributed to RPL's proactive routing nature, which floods the network with DIOs. Due to this, the Selective Forwarding attacking motes (13 and 14) rapidly, but selectively, intercept and forward packets as per their malicious behaviour. Conversely, MRHOF-RPL protocol has no mechanism for detecting Selective Forwarding attacks perpetrated by malicious motes 13 and 14 during the experimentation period.

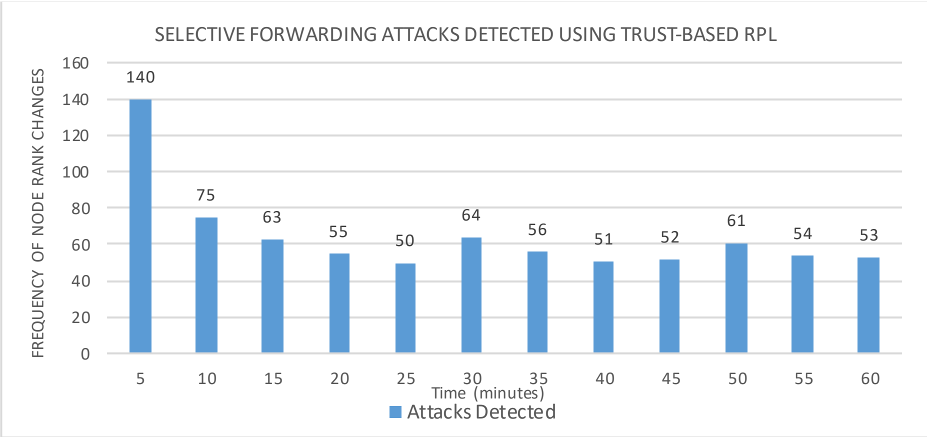

Figure 13. Selective Forwarding attacks detection and isolation during the testbed experiment

Figure 14 shows the frequency of mote Rank changes between MRHOF-RPL and the Trust-based RPL protocol under Selective Forwarding attacks during the testbed operation. MRHOF-RPL had a significant number of mote Rank frequency changes. The frequency of Rank changes for MRHOF-RPL ranged from 122 – 661, while Trust-based RPL had a range of 17 – 200. The MRHOF-RPL protocol under Selective Forwarding attacks reveals high malicious mote activity. Conversely, Trust-based RPL had much lower mote Rank changes, which could be considered moderate and consistent with RPL operations. This implies that the Trust-based RPL had better network performance and stability.

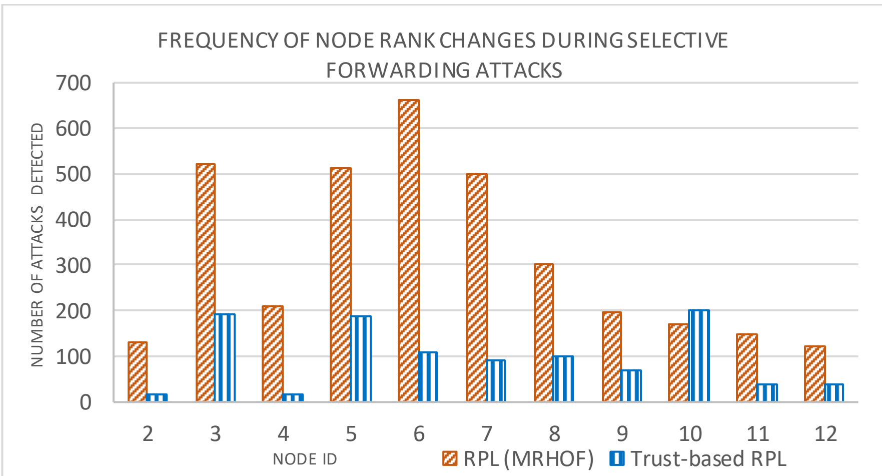

Figure 14. Comparison of frequency of node Rank changes under Selective Forwarding attacks during the testbed experiment

Network Performance Measures

In the throughput comparison between MRHOF-RPL and the Trust-based RPL shown in Figure 15, the Trust-based RPL protocol displayed a better throughput performance over MRHOF-RPL. MRHOF-RPL consistently lagged behind the Trust-based RPL in throughput performance during the testbed trials. Trust-based RPL maintained 4 – 6.5 kbps throughput range, while MRHOF-RPL had a range of 1 – 4 kbps.

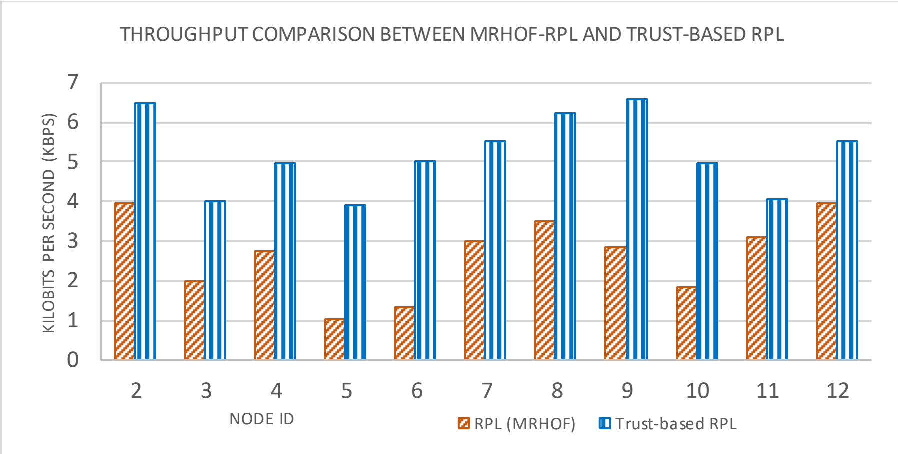

Figure 15. Network throughput performance comparison between Trust-based RPL and MRHOF-RPL during the testbed experiment

Figure 16 shows the packet loss rates between MRHOF-RPL and Trust-based RPL. The Trust-based RPL maintained packet loss rates between 15% – 27.7%; MRHOF-RPL on the other hand, had packet loss rates of 60% – 72.7%. It can be summarised, therefore, from Figure 16, that the Selective Forwarding attacks of malicious motes 13 and 14 had a more significant impact against the MRHOF-RPL network than is the case for the network using the Trust-based RPL protocol. This further shows Trust-based RPL as having better network performance over MRHOF-RPL under the Selective Forwarding attacks.

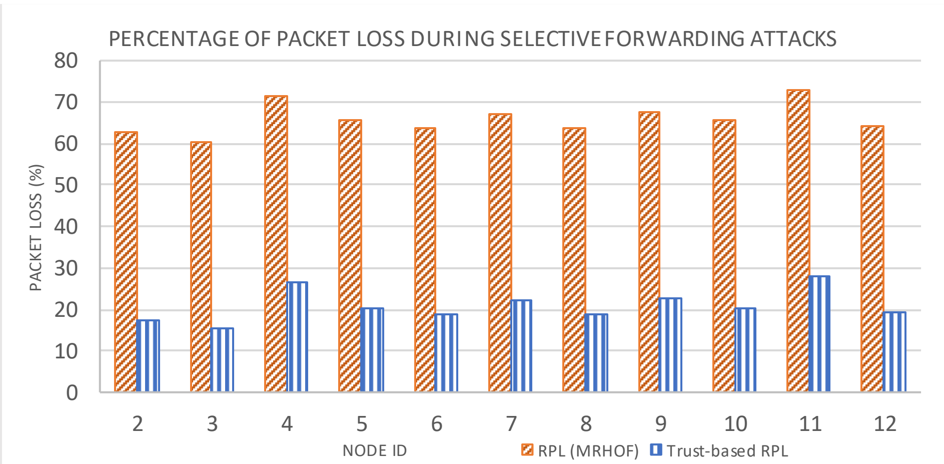

Figure 16. Percentage of packet loss comparison between Trust-based RPL and MRHOF-RPL under Selective Forwarding attacks during the testbed experiment

Conclusions and Future Work

Compromised sensor nodes can destabilize the integrity of data routing in IoT networks by intentionally dropping or sending incorrect control and route information. This study evaluated through testbed experiments the performance of our Trust-based RPL protocol against the standard RPL (MRHOF) protocol under Blackhole and Selective Forwarding attacks. The testbed data gathered were analysed to determine the efficacy of our Trust-based

RPL protocol in mitigating Blackhole and Selective Forwarding attacks in comparison with the IETF standard presented in ContikiRPL. The results gathered through the testbed experiments are in agreement with our simulation study results in Airehrour et al. (2016b) and thus confirm the validity of our Trust-based RPL protocol in terms of providing better security against Blackhole and Selective Forwarding attacks in IoT networks. As part of our future work, we are conducting similar testbed experiments to examine ways of extending our trust-based protocol to address Rank and Sybil attacks, amongst others.

References

Airehrour, D; Gutierrez, J; Ray, SK. 2016a. 'Secure routing for internet of things'. J*ournal of Network and Computer Applications*, vol. 66(C), pp. 198-213. doi:10.1016/j.jnca.2016.03.006

Airehrour, D; Gutierrez, J; Ray, SK. 2016b. 'Securing RPL routing protocol from blackhole attacks using a trust-based mechanism'. 2016 26th International Telecommunication Networks and Applications Conference (ITNAC), 7-9 Dec 2016.

Airehrour, D; Gutierrez, J; Ray, SK. 2017. 'A Trust-Aware RPL Routing Protocol to Detect Blackhole and Selective Forwarding Attacks'. *Australian Journal of Telecommunications and the Digital Economy*, vol. 5, no. 1, pp. 50-69. doi:http://dx.doi.org/10.18080/ajtde.v5n1.88

Djedjig, N; Tandjaoui, D; Medjek, F. 2015. 'Trust-based RPL for the Internet of Things'. 2015 IEEE Symposium on Computers and Communication (ISCC), 6-9 July 2015.

Fortier, PJ; Michel, H. 2002. *Computer Systems Performance Evaluation and Prediction*, Butterworth-Heinemann.

Gaddour, O; Koubâa, A; Abid, M. 2015. 'Quality-of-service aware routing for static and mobile IPv6-based low-power and lossy sensor networks using RPL'. Ad Hoc Networks, vol. 33, pp. 233-256. doi:http://dx.doi.org/10.1016/j.adhoc.2015.05.009

Glissa, G; Rachedi, A; Meddeb, A. 2016. 'A Secure Routing Protocol Based on RPL for Internet of Things'. 2016 IEEE Global Communications Conference (GLOBECOM), 4-8 Dec 2016.

Heurtefeux, K; Erdene-Ochir, O; Mohsin, N; Menouar, H. 2015. 'Enhancing RPL Resilience Against Routing Layer Insider Attacks'. 2015 IEEE 29th International Conference on Advanced Information Networking and Applications, 24-27 March 2015.

Kantert, J; Ringwald, C; Zengen, G. V; Tomforde, S; Wolf, L; Müller-Schloer, C. 2015. 'Enhancing RPL for Robust and Efficient Routing in Challenging Environments'. 2015 IEEE International Conference on Self-Adaptive and Self-Organizing Systems Workshops, 21-25 Sep 2015.

Kasinathan, P; Pastrone, C; Spirito, MA; Vinkovits, M. 2013. 'Denial-of-Service detection in 6LoWPAN based Internet of Things'. 2013 IEEE 9th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), 7-9 Oct 2013.

Kumar, A; Matam, R; Shukla, S. 2016. 'Impact of packet dropping attacks on RPL'. 2016 Fourth International Conference on Parallel, Distributed and Grid Computing (PDGC), 22-24 Dec 2016.

Le, A; Loo, J; Chai, K; Aiash, M. 2016. 'A Specification-Based IDS for Detecting Attacks on RPL-Based Network Topology'. *Information*, vol. 7, no. 2, p. 25.

Mayzaud, A; Badonnel, R; Chrisment, I. 2017. 'A Distributed Monitoring Strategy for Detecting Version Number Attacks in RPL-Based Networks'. *IEEE Transactions on Network and Service Management*, vol. 14, no. 2, pp. 472-486. doi:10.1109/TNSM.2017.2705290

Nawir, M; Amir, A; Yaakob, N; Lynn, OB. 2016. 'Internet of Things (IoT): Taxonomy of security attacks'. 2016 3rd International Conference on Electronic Design (ICED), 11-12 Aug 2016.

Pongle, P; Chavan, G. 2015a. 'Real time intrusion and wormhole attack detection in internet of things'. *International Journal of Computer Applications*, vol. 121, no. 9.

Pongle, P; Chavan, G. 2015b. 'A survey: Attacks on RPL and 6LoWPAN in IoT'. 2015 International Conference on Pervasive Computing (ICPC), 8-10 Jan 2015.

Sehgal, A; Mayzaud, A; Badonnel, R; Chrisment, I; Schönwälder, J. 2014. 'Addressing DODAG inconsistency attacks in RPL networks'. 2014 Global Information Infrastructure and Networking Symposium (GIIS), 15-19 Sep 2014.

Summerville, DH; Zach, KM; Chen, Y. 2015. 'Ultra-lightweight deep packet anomaly detection for Internet of Things devices'. 2015 IEEE 34th International Performance Computing and Communications Conference (IPCCC), 14-16 Dec 2015.

Tan, K; Wu, D; Chan, A; Mohapatra, P. 2010. 'Comparing simulation tools and experimental testbeds for wireless mesh networks'. 2010 IEEE International Symposium on "A World of Wireless, Mobile and Multimedia Networks" (WoWMoM), 14-17 June 2010.

Taylor, C; Johnson, T. 2015. 'Strong authentication countermeasures using dynamic keying for sinkhole and distance spoofing attacks in smart grid networks'. 2015 IEEE Wireless Communications and Networking Conference (WCNC), 9-12 March 2015.

Thingsquare. 2016. 'Contiki: The Open Source OS for the Internet of Things'. Available from http://www.contiki-os.org/download.html

http://doi.org/10.18080/ajtde.v6n1.138

Winter, T; Thubert, P (Eds). 2012. 'RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks'. Internet Engineering Task Force (IETF), RFC 6550. Available from https://tools.ietf.org/html/rfc6550 .

Vale Roger Banks: A Tribute

Edgar Roger Banks, 10 July 1930 – 26 January 2018

Jim Holmes
Incyte Consulting

Abstract: Roger Banks, who was well known to many in the telecommunications industry, passed away in January 2018. He retired as Telecom Australia's Director of Business Development in 1988, having made significant contributions to Telecom's commercial development and customer focus. His early career included significant leadership in CCITT's switching studies. This obituary outlines his life from the early days in Victoria, through his career with the PMG and Telecom, to his post-retirement contributions as a board member and supporter of engineering education.

Keywords: Roger Banks; obituary

Introduction

Roger Banks, who was well known to many in the telecommunications industry, not only for his work in Australia but internationally, passed away suddenly in January this year. It is some time since Roger retired from Telecom Australia and this obituary seeks to record the work that he did and the contribution that he made professionally and personally as a tribute to him.

The early years: 1930 – joining the PMG

Those who knew Roger well will mostly recall a very congenial and outgoing personality. Roger spoke in a clipped voice and gave the impression that he might have been born in England. In fact, when he told this author of his early days in Brighton, I initially assumed that he meant Brighton, UK, but he really meant Brighton, Melbourne. However, his parents had only recently arrived from England by the time he was born. Roger's father, Raymond, was an electrical engineering graduate from Birmingham University who had joined the British General Electric Company and was sent to Australia in 1928 as branch manager in Perth and then Melbourne. Raymond married shortly after, and Roger was his first child, in July 1930.

Roger attended Brighton Grammar until 1948 where he was school captain and dux. He shone intellectually and as a leader, and was a good all-rounder in sport. Following school, Roger became a PMG (Postmaster General's Department) cadet, with an associated scholarship to Melbourne University to study electrical engineering. After two years, he transferred to full-time study and graduated with a bachelor's degree in 1953.

From maintenance in western Victoria to the CCITT

Roger's initial assignments with the PMG were in long line work in western Victoria, and included specialised tension work on telegraph wires in the Bendigo area and other lines maintenance work from Geelong to the South Australian border. The PMG was organised on State lines in those days, and bore the clear organisational traces of its origins as an assembly of Colonial Post Offices until 1988. He did not hide his light under a bushel in western Victoria, however, and wrote a paper on line-work repair practices to gain some visibility in the organisation. It clearly worked, because he was called on to assist in fault repair operations on the systems connecting Perth and Adelaide. In addition, he gained promotion from Engineer Grade 1 to Grade 3.

In 1955 Roger won a public service scholarship for young engineers, which enabled him to go to the United Kingdom to study developments in switching technology. Roger's specific program involved spending around three months with each of five companies that were involved in crossbar switching developments at the time, including GEC, STC and the British subsidiaries of Ericsson and Siemens.

While in the UK Roger met his future wife, Molly, and they married in 1956 in Melbourne.

Roger developed substantial knowledge of switching technology during his overseas scholarship and subsequently was well placed later to assist the PMG in selecting the main vendor for its own crossbar system. The tender for automatic crossbar switching systems for major telephone exchanges was a significant development amongst telecommunications operators worldwide in the 1950s and 1960s. The Australian PMG chose the Ericsson system.

Roger wrote a detailed paper on crossbar switching, which was published in this *Journal* in 1961 and is reprinted in this issue. In later years, the Ericsson AXE, whose development flowed from Ericsson's global switching initiatives at this time, became the primary switch in the PMG's and later Telecom Australia's network until the 1980s, when stored program controlled and other digital switching technologies were adopted. In the wider world, crossbar continued to be the major switching technology for much longer, particularly in developing economies.

From 1961 Roger participated as an Australian representative in the work of the International Telecommunications Union (ITU). Because of his work at the forefront of switching and engineering planning, he was appointed as chairman of the CCITT Special Autonomous Group on National Automatic Networks from 1965 until 1968. (CCITT was the Consultative Committee for International Telegraphy and Telephony of the ITU.) CCITT work was part-time and the various Working Groups and Special Autonomous Groups met at various places, but mostly Geneva, throughout the year to progress their standardisation and development work. During the period in which Roger chaired the Group, it met in Montreal, New York, Stockholm, Munich, Tokyo and Melbourne, as well as in Geneva.

Figure 1. Roger Banks (second from right) chairing a CCITT Special Autonomous Group meeting in Tokyo in 1967.

One of the achievements of the Group was the completion and publication of a handbook called the *Manual of National Automatic Networks*. In June 1964, Roger presented the Group's plenary report in Geneva. The Handbook was published in 1964 in the official languages of the ITU: English, French and Spanish. Within the ITU, the Handbook became something of a "best seller" and an important source of advice for engineering switching planning and operations, particularly in developing countries. Even in the late 1990s, when digitalisation was well underway, regulators and engineers from developing countries mentioned to this author their continuing indebtedness to the Handbook for assisting their work. Roger was able to facilitate cooperation within groups such as the Special Autonomous Group by his continuing engagement with people and unfailing good humour, and sense of humour. He was invariably regarded as a pleasure to work with, and this extended to all of his personal and professional dealings with others.

In the mid-1950s, the PMG resolved to develop and implement a national telephone plan for the transformation of the Australian system to an automated national network with an integrated automatic dialling system (Moyal 1984, pp. 223-224). At last the State-based organisations reflecting the historically diverse approaches of Australia's separate colonial administrations would be integrated in technical and operating terms suited to the times. The Automatic Network and Switching Objectives (ANSO) committee was established within the PMG under Ron Turnbull, superintending engineer. A more comprehensive and integrated approach to national planning developed as a result, and the Community Telephone Plan was launched in 1960.

Roger contributed to the national planning function during the 1960s, including the implementation of the Community Telephone Plan. He later was a member of the team responsible for the introduction of Australia's first computer-controlled trunk switching technology (known as 10C) in 1969.

New horizons in the UK and Australia

In 1972, Roger made a major career decision and decided to resign from the PMG and accept an invitation from the chairman of Plessey Telecommunications in the UK to become that company's director of strategic planning, based in Liverpool. Roger had come to notice through his work both in Australia and internationally on planning and switching. At the time, Plessey was developing its computer-controlled switching systems and faced stiff competition in both British and international market places. Roger moved with his family (including by then two school-age children, Melissa and Jeremy) to the UK towards the end of that year.

It turned out not to be a good decision. Roger saw that the experiment was not working out and chose to rejoin the PMG where he was welcomed back by the Director-General, Eber Lane. He returned in 1974 and his appointment was gazetted as an Engineer Class 1. However, within a week he was promoted from Engineer Class 1 to a senior managerial position at Level 2, Second Division. In other circumstances, this would have been a meteoric rise and, even as it was, it was remarkable.

Marketing and customer service

When Roger returned to Australia, the PMG was in considerable turmoil, planning for the separation of the organisation into two arms-length Government Business Enterprises, structured as Commissions, to carry out postal and telecommunications business, respectively, and a residual department of state. This followed the inquiry by the Vernon Commission into the Australian Post Office and the Government's acceptance of its recommendations in April 1974. The new organisations were to commence operation on 1 July

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1975 and much planning and negotiation was needed to have the legislation and the arrangements in place by that deadline. Roger participated in the process and was appointed as General Manager, Customer Services in the new Australian Telecommunications Commission (trading as Telecom Australia).

This was a new role entirely for Roger and an unusual one. The monopoly businesses of Telecom were preserved by legislation, but were by no means secure. Telecommunications monopolies were under challenge in both the United States and the United Kingdom, and in many respects Telecom's performance in delivering low cost, high quality services needed considerable improvement. It was Roger's role and that of his new department to ensure that Telecom developed a commercial culture, and not just an engineering one as in the past. In the period immediately after 1975, much was attempted in terms of strengthening local management (the District organisation), developing customer management and marketing systems, improving billing and other back-office systems, and developing new and innovative products and services, especially in terms of data and text communications. Much was attempted, but the results were mixed. Telecom was a large organisation, with many forms of inertia and internal diversity. As other articles in this *Journal* have shown, changing culture in such circumstances is a complex and often protracted process.

Business Development

In 1980, Roger became Telecom's Director of Business Development. In the next several years Telecom sought to transform its operations and culture further and faster, in response to the proposed market liberalisation and competition recommended by the Davidson Inquiry, and later to the actual competition introduced by the Hawke-Keating Government in the late 1980s. Until the early 1980s, Telecom business planning and development processes were undeveloped and not explicitly commercial. Roger's new role involved rectifying this and bringing a strategic focus to bear. In that role, he recognised that many of the policy and business settings in which Telecom was operating needed to change, and that they were not always matters that should be left entirely to Government.

He recognised the potential importance of mobile telecommunications and the need for Telecom to be at the forefront of developments in Australia. When appointed to the Business Development position, Roger was one of the very few people who highlighted that Telecom's commissioning of the PAMTS (Public Automatic Mobile Telephone System) mobile telephone system in 1981 was too slow and inadequate, particularly as the Davidson Inquiry was being launched in 1981. A suitable cellular mobile system was not commissioned by Telecom until 1987, well after comparable countries.

Roger also took a lead on addressing the issues associated with untimed local calls, calling for a review and the introduction of some limitations. The issue proved to be extremely controversial, which was taken up by political parties in an extremely partisan way. It has been widely blamed for the ALP government's loss of the long-held seat of Adelaide at a by-election in February 1988. The media singled out Roger as the major Telecom spokesman on the matter.

Figure 2. Roger Banks as Telecom's Director of Business Development, 1986.

The Government determined from the mid-1980s to use competitive policy settings and further reorganisation to transform the telecommunications sector. The initial stages were reflected in the arrangements in the Telecommunications Acts of 1986 and 1988. Roger considered that this offered a suitable and appropriate opportunity to pass the baton to others. He retired from Telecom in 1988, after a career of substantial achievement.

Retirement?

Roger's retirement was filled with substantial community involvement and service. He continued to participate in the councils of Brighton Grammar. He was an RACV councillor from 1992 to 2001 and RACV President from 1990 to 1993; a Vic Roads Board member from 1992 to 2005, and a Board member of the Monash University Accident Research Centre in 2005.

Roger was the honorary chairman of the Melbourne University Engineering Foundation from 1997 to 2007 and was awarded a doctorate *honoris causa* for his contribution to engineering and engineering education by Melbourne University in 2003. Roger took great pride in receiving that honour.

During his post-Telecom years, Roger also undertook various consulting tasks promoting local telecommunications and IT firms. This was often undertaken in the role of good citizen.

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In more recent years, Roger became increasingly a carer for Molly until she was admitted to a care facility as her dementia progressed.

Roger was his ebullient and sociable self, in good health and spirits up to the day of his death. He passed away in his sleep during the night of 25 January this year. He will be sadly missed by his friends and family and the countless telecommunications workers and engineering students to whom he gave support, encouragement and guidance over many years.

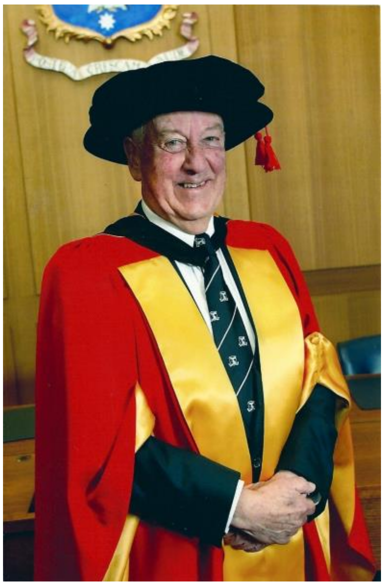

Figure 3. Roger Banks when receiving an honorary D.Eng. from the University of Melbourne in 2003.

Acknowledgements

This tribute to Roger has been prepared with the assistance of his daughter, Melissa, and son, Jeremy, and of former colleagues who worked with Roger in the PMG and Telecom Australia.

References

Moyal, Ann. 1984. *Clear Across Australia: a history of telecommunications*, Melbourne: Thomas Nelson.

Introduction of Crossbar Switching Equipment to the Australian Telephone Network

Simon Moorhead
Ericsson Australia and New Zealand

Abstract: A historic paper from the Journal in 1961 summarising the investigation and selection of Crossbar Switching Equipment for the Australian Telephone Network.

Keywords: Telecommunications, History, Crossbar Switching Equipment, Australian Telephone Network

Introduction

Around the end of 1959, the Australian Post Office (APO, later split into Telecom Australia and Australia Post) made the decision to standardise on the L M Ericsson register-controlled crossbar switching system for the Australian Telephone Network. This was a controversial decision given the entrenched position of step-by-step equipment with its British heritage. The historic paper (Banks E. R. 1961) details the rigorous investigations over the previous three years to "identify the type of switching system best suited to the requirements for economic and efficient expansion of the Australian Telephone Network".

The paper comprises three parts, namely:

1. the circumstances leading up to the investigation and the factors underlying the analysis and decisions;
2. the system adopted; and
3. the way in which the equipment will be integrated into the network.

It is evident to the reader that the APO were extremely thorough in their investigations and mindful of the need to accommodate a trebling of the subscriber numbers in the next twenty years. Similarly, the equipment needed to support future subscriber trunk dialling and the separation of routing and dialling for increased efficiency.

A number of key requirements were identified and used to rank the switching system alternatives. Taking all these requirements into consideration, it was clear that the most desirable switching system for use in the Australian network was a link-trunked crossbar system. The crossbar system was fully developed and tried in local, rural and trunk transit applications and worked successfully with step-by-step networks. Of the systems on offer, the L M Ericsson register-controlled crossbar equipment was chosen as most nearly fulfilling the requirements.

Initially, the Ericsson crossbar switches were manufactured under licence by STC and TEI in Australia, who were supplying the step-by-step equipment at that time. In 1960, Ericsson purchased Trimax Transformers Pty Ltd, which was renamed L M Ericsson Pty Ltd (Ericsson Australia) in 1963. Soon after, a new production plant was built by Ericsson at Broadmeadows in Victoria (Spongberg, C. A. 1967) and was the subject of a previous historic paper in this *Journal* (Moorhead S. 2015), which resulted in Ericsson capturing one third of the market for public telephone exchanges in Australia.

References

Banks E. R. 1961. 'Crossbar Switching Equipment for the Australian Telephone Network', *Telecommunication Journal of Australia*, Vol. 13, No. 2, October 1961, pp. 85-113.

Spongberg, C. A. 1967. 'Establishing L. M. Ericsson Crossbar Production in Australia', *Telecommunication Journal of Australia* Vol. 17, No. 2, June 1967.

Moorhead S. 2015. 'Ericsson Celebrates 125 Years in Australia', *Australian Journal of Telecommunications and the Digital Economy*, Vol. 3, No. 4, December 2015.

http://doi.org/10.18080/ajtde.v6n1.145

The Historic Paper

E. R. BANKS

E. R. BANKS, author of the article "Crossbar Switching Equipment for the Australian Telephone Network" joined the Department in 1948 as a Cadet Engineer and completed his training and the Degree of B.E.E. at Melbourne University in 1952. In this year, Mr. Banks shared the Dixson Scholarship in Electrical Engineering and won Monash, Newbigin, and Oral Presentation prizes of the Institution of Engineers Australia for two papers, one on Network Design and one on the Electrolytic Tank. After nine months on Country Installation work in Victoria Mr. Banks joined the Long Line Equipment Section at Central Office and was assigned the task of locating an intermittent fault on the Adelaide/Perth section of the Sydney Cottesloe high speed telegraph circuit. Following the successful completion of this assignment Mr. Banks spent 1955 and 1956 in England and Europe as the holder of a scholarship from the Federation of British Industries. During this time he visited and worked with Telecommunication Manufacturers and the British Post Office. On his return from England Mr. Banks took up duty as Divisional Engineer, Traffic, in the Telephone Equipment Section and later as Sectional Engineer, Network Planning. He was associated with the re-issue of Traffic Engineering Instructions as Chairman of the Traffic Engineering Committee and with the studies and work leading to the recommendation that the Department adopt Crossbar as the new standard switching system. Currently Mr. Banks is Chairman of the C.C.I.T.T. Working Party on National Automatic Telephone Networks with the responsibility for formulating guiding principles to assist new and developing countries in the development of their automatic telephone networks. Mr. Banks is an Associate Member of the Institution of Engineers Australia and an Editor of this Journal.

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CROSSBAR SWITCHING EQUIPMENT FOR THE AUSTRALIAN TELEPHONE NETWORK

*E. R. BANKS, B.E.E., A.M.I.E.Aust.**

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INTRODUCTION

This paper is intended as a summary of an investigation carried out over the past three years into the type of switching system best suited to meet the requirement for economic and efficient expansion of the Australian Telephone Network. As a result of this work, a register-controlled crossbar switching system of L. M. Ericsson design was adopted as standard. Part I of the paper describes briefly the circumstances leading up to the investigation and the factors underlying the analysis and decision. Part II describes the system adopted and Part III indicates the way in which the equipment will be integrated into the network.

PART I.—CHOICE OF A SYSTEM

Local Network Problem

Since the first automatic exchange was installed in Geelong (Victoria) in 1912, the Post Office has progressively developed the automatic local networks using step-by-step equipment and employing the Strowger and, later, the British 2,000 type and SE.50 bimotional selectors. Step-by-step control is one of the earliest and most widespread methods of automatic switching and had its origin in the invention by Strowger of the 100-point selector (see Fig. 1). A group of these basic units can be used for a 100-line exchange. As the network develops succeeding stages are added for each digit required, and it is readily apparent that such a system is inflexible (see Fig. 2). The routing of a call is tied to the numbering, and a given block of numbers can be used only in a certain area. Development of a network of the type shown in Fig. 2 can proceed without serious difficulty until the numbering limitations of six-digit working, a practical capacity of about 500,000 subscribers, are approached. By 1956 the Melbourne and Sydney networks were nearing saturation on a six-digit number basis following the very rapid post-war development, and the cost of converting to seven-digit working, where required, was estimated at up to £6 extra per subscriber's line for the necessary additional switching stage.

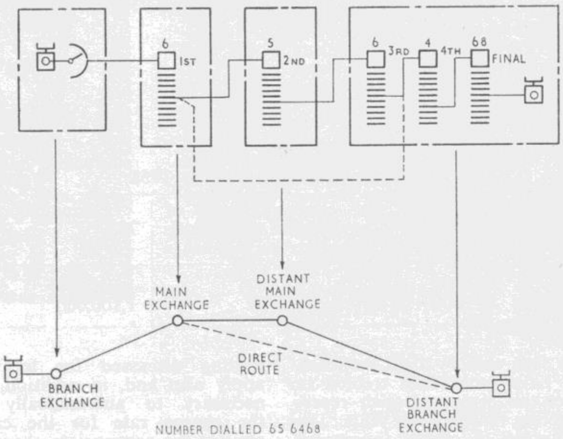


Fig. 2.—Call Routing in a Step-by-Step Network.

The prospect of adding another switching stage also implied the upgrading of all links between existing switching stages in order to maintain the existing overall grade of service provided to subscribers. The grade of service or probability of call loss over the complete connection is, to a first approximation, the sum of the loss probabilities in each link and, therefore, the addition of an extra link would require extra circuit provision on all previous links. Finally, impulses are repeated forward in a step-by-step network from exchange to exchange. The consequent restrictions on signalling limits on both subscribers' and junction lines necessary to minimise impulse distortion and ensure successful operation of the switch at the distant exchange were proving a serious economic and technical limitation with the present equipment.

Considerable savings were seen to be possible by the removal of the basic restriction that routing and numbering are tied together. Use could be made of a given group of junctions for two traffic loads, one of which occurred during the day and the other at night, whereas at present, for example, the junction plant in the city areas is practically idle during the night, whilst the reverse is true in residential areas. A second result of divorcing routing from numbering would be that traffic could be moved between two exchanges on the most economic route rather than over a rigid backbone of links and switches. In many instances this would mean the bypassing of several intermediate switching stages and consequent plant savings. For example, in Fig. 2 the dotted route from the first selectors direct to the fourth selectors could carry traffic destined for any one of 1,000 subscribers, bypassing two switching stages.

A limited amount of direct routing had already been possible with step-by-step equipment but only within the main exchange group of the calling subscriber.

*See page 154.

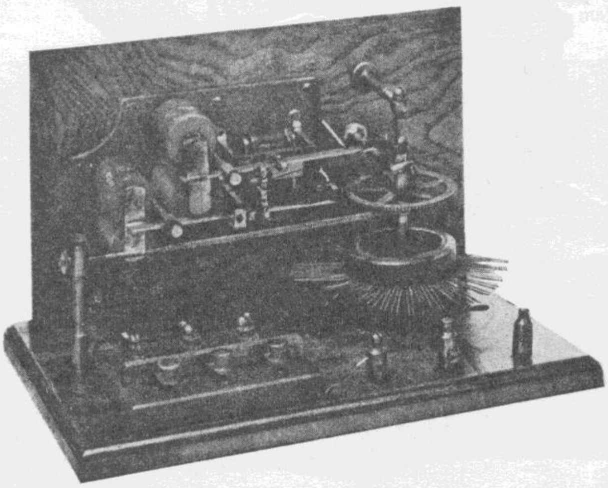


Fig. 1.—Original Strowger Switch, 1892.

It was clear that the possibilities for effecting considerable economies existed if a flexible and universal system of direct routing could be introduced. Improvement in signalling methods would also remove signalling limitations on junctions and subscriber's lines.

These technical possibilities for economic expansion in the local networks can be seen to possess real potential in terms of possible capital savings when the rates of growth in the Melbourne and Sydney networks are considered. Table I shows the present size and expected growth of these networks.

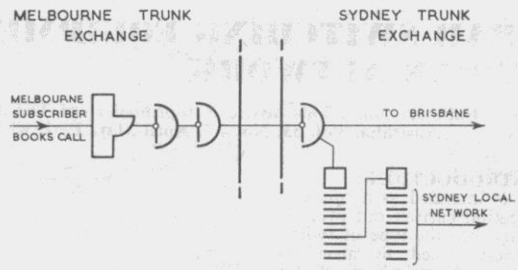


Fig. 3.—Trunk Connection, Melbourne to Sydney.

TABLE I.
Development Statement at 1958

Network	Numbers in use 1958	Present average rate of provision of additional numbers per annum	Estimated at 1980	
			Total	Rate of growth per annum
Sydney	332,000	25,000	1,124,000	79,000
Melbourne	273,000	20,000	1,100,000	77,000

It can be seen that by 1980 both networks will have more than trebled in size, in fact the present growth represents a doubling in every ten years. The major proportion of capital investment in the exchange and junction sections of a network is vested in the junctions, cable and conduits. The proportion at present is about 70 per cent. It is clear, therefore, that there is considerable scope for effecting economies in investment by adopting a switching system which will allow traffic to be carried over the shortest possible route to its destination.

Trunk Network

Since 1940, with the installation of semi-automatic transit trunk switching in Melbourne, the long distance trunk network has been developed using transit switching to eliminate the distant operator on long-distance calls. Fig. 3 shows a simple schematic of the routing for a trunk call from Melbourne to Sydney. The Melbourne trunk operator can dial direct to the subscriber in the Sydney network without the assistance of the Sydney telephonist. This mode of operation has been introduced at capital cities and provincial centres throughout the Commonwealth in the past 20 years. However, the growth of trunk traffic and the increasing cost of manual operation, together with the development of techniques in recent years to provide economically large blocks of long-distance channels by coaxial cable or radio, now make it feasible and necessary to consider the extension of subscriber control into the long-distance network. For subscriber-dialling of trunk traffic, Australia-wide numbering and charging schemes are necessary in order to simplify directory presentation and switching system design and operation. The study and development of a plan aimed at developing the Australian network for ultimate subscriber-dialling of all calls was commenced in 1956. This study soon highlighted the limitations of the present switching equipment in meeting this objective economically. In the Trunk Network the requirements for routing discussed for local networks apply also and, in addition, it will be necessary to automatically determine the charge rate for the call and to register the appropriate charge information on the subscriber's meter. The national number will be the local number plus between one and three national digits, and this eight-digit number must be received and interpreted by the switching equipment. For long built-up connections a high quality circuit must be assured, especially once the operator is removed altogether and is not available to reject the occasional noisy or low-volume connection, as she may do at present.

Rural Networks

The third problem facing the Post Office was the economic extension of continuous automatic service to rural

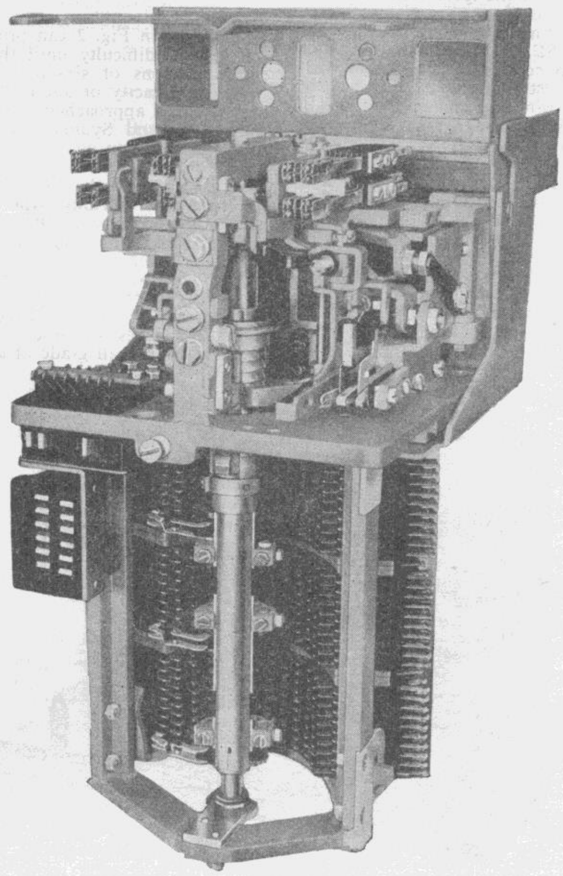


Fig. 4.—Bimotional Selector.

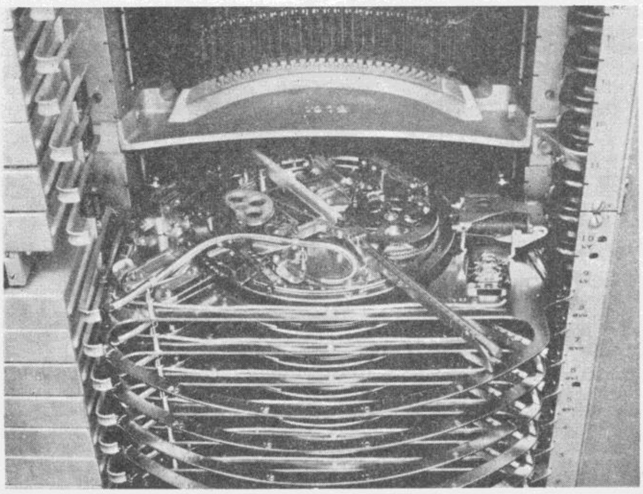


Fig. 5.—500-Line Selector.

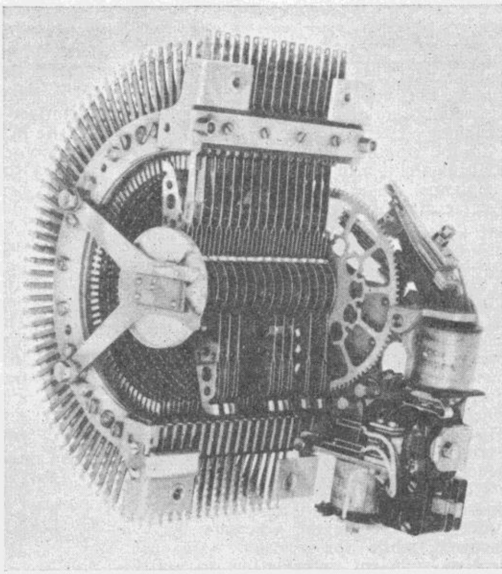


Fig. 6.—Motor Uniselector.

subscribers. The installation of the Rural Automatic Exchange (R.A.X.) in the post-war period went a long way towards eliminating the small manual exchanges of 200 lines or less. However, these units provided automatic access only between subscribers on the exchange in question, and the majority of these exchanges had as a parent the local provincial exchange, which was manual. With the proposal to introduce a national numbering plan and extended dialling, and to remove manual working, it became apparent that the present R.A.X., due to its design and trunking, could not be integrated readily in the closed-numbering areas proposed for these districts. Furthermore, the outstanding problem in the rural areas was the medium-size provincial town with an exchange of 200-1,000 lines for which Magneto or Common Battery (C.B.) manual equipment was being employed. Here, as in the trunk exchanges, the costs of operation and telephonists' facilities were rising to the level where it was economic to consider automatising the system. In these areas subscriber distance-dialling and automatic multi-metering were essential, and the step-by-step automatic switching equipment currently used in the large cities was not capable of providing for the economic introduction of such a scheme.

These three sectors of the network, local, trunk and rural, were therefore all in need of a new switching system which would facilitate economic expansion and provide for the ultimate complete automatisation of the system. To meet this requirement, a detailed examination of the various available switching systems was undertaken with a view to selecting the one most suited for the immediate and long-term Australian requirements.

Switching System Types

It is necessary at this stage to pause and review very briefly the main types of electromechanical switching systems which have been employed in telephone exchanges in the past 50 years.

Switching systems consist essentially of two elements, the switches or speech path connecting devices, and the controls. These controls are either concentrated in common units taken into use only to set the switches, or small control elements are permanently associated with each switch. The latter principle is usually termed step-by-step operation since the successive switches each take one digit and route the call one stage further.

These systems can be classified in four main categories identified by the type of switch employed:—

(i) The Bimotional Selector (Fig. 4), developed from the original Strowger patent, is used extensively in step-by-step switching systems and in the director system which employs a common translating register.

(ii) The 500-point Planar Switch (Fig. 5) is used in a register-controlled common-drive system on the rotate and thrust principle.

(iii) The Motor Uniselector (Fig. 6), developed by Siemens & Halske later by Siemens Bros., England (now A.E.I., Woolwich), has 16 arcs and 52 contacts per arc, providing a maximum of 200 four-wire outlets. This switch has been used in step-by-step and register-controlled systems, and may employ common drive as in the Rotary Systems used extensively in Belgium and France.

(iv) The Crossbar Switch (Fig. 7), developed from the patents of Betulander in 1896, has been used in both step-by-step and register systems, and has received increasing attention in recent years.

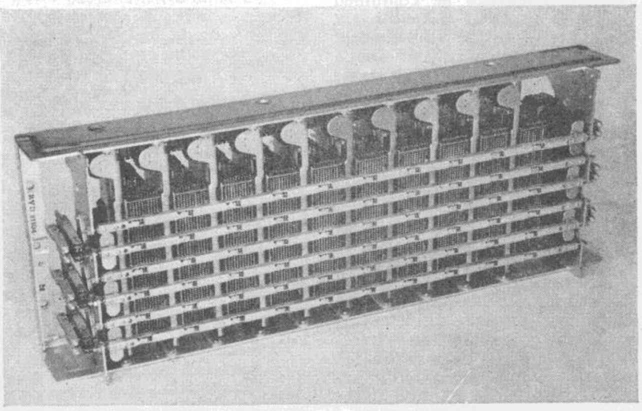


Fig. 7.—Crossbar Switch.

Register Control

The separation of call routing from the number dialled was seen as the fundamental requirement of the new system, and could only be achieved by the adoption of a register-controlled switching system.

In the original manual exchange the control intelligence was embodied in the telephonist. She identified the calling line, received from the caller the number he required, connected the call by the most direct available route and registered on a docket the appropriate charge. With the introduction of step-by-step working, the operator's intelligence was in effect distributed throughout the system. Each switch performed a small part of the routing function, and the meter associated with the subscriber's line switch registered the unit call charge when the called subscriber answered. The common control or register type exchange collects this control intelligence once more into a centralised unit.

Common controls require high-speed operation and high-speed signalling in order to overcome the necessary delay incurred while the register waits to receive sufficient information to start work. The development of reliable and fast-operating controls, providing rapid call connection and, at the same time, competing economically with the simpler step-by-step system, originated in the immediate pre-war era and, receiving considerable impetus from the technological developments of the 1939-45 period, have expanded rapidly since the war.

The London Director system is an example of register control applied to bimotional selectors. The required number is examined in the register and a routing code is pulsed into the step-by-step switching system. This code will vary depending on where in the network the caller originates his call. The problem here is that this routing code is pulsed out of the register at 10 c.p.s., the normal dialling speed, and delays after dialling of up to 20 seconds may result before the connection is established and ring is fed to both subscribers. Further, the "director", as the register is called cannot vary the route taken by the call to take advantage of changes in circuit loading with time. The programme is rigid, and routing is still tied to the numbering allotted to the routing code. The planar 500-point system is also slow, due primarily to the speed of setting of the large switch. The two electromechanical switching principles suitable for register control which have received the greatest attention in recent years have been the Crossbar and the Motor Uniselector.

System Comparison

Systems using these two techniques were closely compared during the study, and the crossbar principle chosen. Concurrently, the various crossbar systems were examined, and as a result, the register-controlled crossbar system employing linked trunking and developed by L. M. Ericsson, Sweden, was finally selected as the type of switching system best able to meet the A.P.O. requirements for the next 10-15 years. These decisions were taken after examining the available crossbar and motor uniselector systems against five basic criteria. It was considered that the system chosen should:—

(i) **Meet the Required Facilities and be in an Advanced Stage of Development:**
- (a) Routing independent of numbering, economic and flexible alternate routing.
- (b) Charging determination and registration for national dialling.
- (c) High-speed operation, minimum post-dialling delays.
- (d) The system should be developed and proved in service in the local, rural and trunk transit sectors of a network, and should have interworked successfully with step-by-step equipment.

(ii) **Comply with Modern Technical Performance Standards:**
- (a) Signalling and Transmission performance should take maximum advantage of the latest developments in these fields.

(iii) **Be Suitable for Economic Local Manufacture.**

(iv) **Be Economic to Install and Maintain.**

(v) **Be Adaptable to Future Developments and, in particular, Electronics.**

These points will now be discussed and the two systems compared. In all comparisons reference is confined to systems in which the switches are used efficiently.

Facilities and Stage of Development

Alternate Routing: Both systems are available with register control and, therefore, routing can be made independent of numbering. As discussed above, the desirable situation is to be able to select for a given call the most direct route to the required destination. It can also be shown that the most economic arrangement of junctions in a network is one in which only the base load of traffic is carried on the direct circuits, the peaks being routed on the backbone route via the tandem exchange. In this way, overflows of traffic from several direct routes can be combined on the backbone route to make efficient use of the circuits. In fact, the concept of marginal utility is introduced and a specification developed such that traffic is carried on the direct route by the addition of circuits until the cost per unit of traffic (Erlang) of carrying the traffic direct is equal to the cost of carrying the traffic on the backbone route. Fig. 8 illustrates this principle of alternate routing.

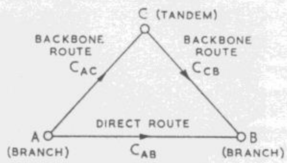
Studies in large networks, such as Sydney and Melbourne, indicate that, to take the fullest advantage of this alternate routing principle, any given call may require to be routed over one of up to four choices, that is, direct, first alternate, second alternate, and backbone. Further, it has been estimated that the total circuit accessibility required may vary between 500 and 1,000, depending on the size of the exchange. To ensure efficient operation in an alternate routed network, it is necessary that a choice be made of a suitable free circuit from all the possible available circuits on each of the four routes with a minimum of delay. To achieve this objective at a switching stage with minimum post-dialling delay, the equipment should be capable of:—

- (i) having prior knowledge of the traffic conditions on each of the possible routes;
- (ii) selecting at high speed a free circuit on a suitable route;
- (iii) positioning or setting the switch at high speed on the selected outlet.

The most efficient method of storing prior knowledge of circuits is to use a single common equipment which controls the operation of a single switching stage which has access to all routes from the exchange. Crossbar switches meet this requirement since they can be arranged in "link-trunked" arrays to provide any desired availability, and the two or three stage array can be set and controlled by a single marker unit. This concept of link-trunking will be further discussed below. However, motor uniselectors have a limited availability of 200 from a given switching stage and, to obtain larger availabilities, a further stage must be added. Attempts to control two stages of motor uniselectors simultaneously have proved complex and uneconomic, and have been abandoned in favour of sequential stage-by-stage setting. This stage-by-stage control means that, after an indication has been received, each switch must be set in turn, whereas the crossbar selectors can be operated simultaneously in about 40 milliseconds compared with about 360 milliseconds for the motor switches.

Testing of circuits in the crossbar system is electrical and is carried out by the marker. There is therefore no limitation to the number of circuits over which the hunt may be carried out. With the motor uniselector, however, the switch hunts at 200 steps per second. Therefore, to test a group of 50 trunks some 250 milliseconds are required compared with some 70 milliseconds for the crossbar scan.

Summing up, the crossbar switch is capable of providing single switching



C_{AB}, C_{AC}, C_{CB} COST OF CIRCUITS ON THESE ROUTES.

${}_{N}E_{AB}$ TRAFFIC CARRIED ON N^{TH} CIRCUIT ON DIRECT ROUTE.

$E_{\overline{ACB}}$, ADDITIONAL TRAFFIC WHICH MAY BE OFFERED TO ROUTE $\overline{ACB}$ WHEN AN EXTRA CIRCUIT IS ADDED, TO PRESERVE THE SAME GRADE OF SERVICE ON THE ROUTE.

CIRCUITS ARE ADDED TO ROUTE AB UNTIL

$$\frac{C_{AB}}{{}_{N}E_{AB}} \geqslant \frac{C_{AC} + C_{CB}}{E_{\overline{ACB}}}$$

Fig. 8.—Principle of Alternate Routing.

stages of any desired availability under a single control, is faster in testing for free circuits and faster in establishing the final connection.

Charging: Charge determination and registration is possible with both systems, and depends primarily on the design of the register equipment.

Stage of Development: One of the primary considerations in selecting the particular crossbar system to be adopted was the extent to which it had been engineered and proved in service. When a new switching principle is devised and a new exchange system is developed, the first step is the construction and testing of a laboratory model or, more often, a private automatic exchange (P.A.X.) to be used in the factory of the developing manufacturer. The model having been successfully proved, the equipment is then ready for application to public networks. This next step may take up to 10 years, during which time the manufacturer and his customers must invest considerable engineering and design effort in the adaptation of the prototype exchange to the three sectors of a communications network, local, rural and trunk, and the solution of all the various interworking problems which will arise when any new plant is grafted on to existing equipment.

The objective in this study was to choose a system which would require the minimum redesign and adaptation in order to take maximum advantage of technology overseas and conserve our own limited resources for the not inconsiderable task of carrying out the inevitable interworking redesign which would be necessary. A switching system is a developed entity ready and tried for application to all three fields, whereas an exchange principle is the nucleus of the system. Of the available crossbar types the one chosen appeared on the evidence available, and, in the opinion of the author and other Post Office engineers who had visited overseas administrations and manufacturers, to be the most thoroughly developed and tested system available.

Technical Standards

One of the vital considerations was that the switching system chosen should possess a low psophometric noise characteristic. A built-up telephone connection consists of a large number of dry metal-to-metal contacts such as relay springs, switch wipers and switch banks. Across each contact there is a small potential difference which, under conditions of vibration, may generate a noise e.m.f. The problem is to ensure that the total noise on the circuit, which consists of the sum of the contributions from each contact, is kept to an acceptable level to ensure a good standard of transmission. This has important economic as well as aesthetic aspects since the speed at which information can be passed and comprehended is related to the signal-to-noise ratio of the channel.

In an endeavour to reduce circuit noise in nation-wide dialling networks, manufacturers of modern switching systems have introduced noble metal pressure contacts for the speech path connections. The quality of these contacts is of particular importance in Australia, due to the "ribbon" nature of our main line network and the large number of transit switching points which may be in tandem on a trunk call. Crossbar switches, due to the relay-like nature of their operation, used pressure contacts, and the contact material is a noble metal. The German E.M.D. motor uniselector was redesigned to use pressure contacts of noble metal in the speech path but the British motor uniselector still employs base metal high-pressure wiping contacts (see Fig. 6).

The present equipment, using base metal rubbing contacts, has a relatively poor noise performance by modern standards, and regular bank cleaning is necessary to minimise noise interference. Noble metal pressure contacts used on crossbar switches, have a resistance of a fraction of an ohm compared with resistances of 1 to 4 ohms after one million operations in the case of base metal rubbing contacts.

The method of signalling in a register network takes a different form from that in a step-by-step direct impulsing network. The routing information is passed between registers using high-speed coded voice frequency signals at a speed of 10 digits per second. This removes the restrictions on network development formerly imposed by the necessity to repeat impulses forward stage by stage. Only the line or supervisory signalling remains associated with the particular junctions. Thus, the resistance limits

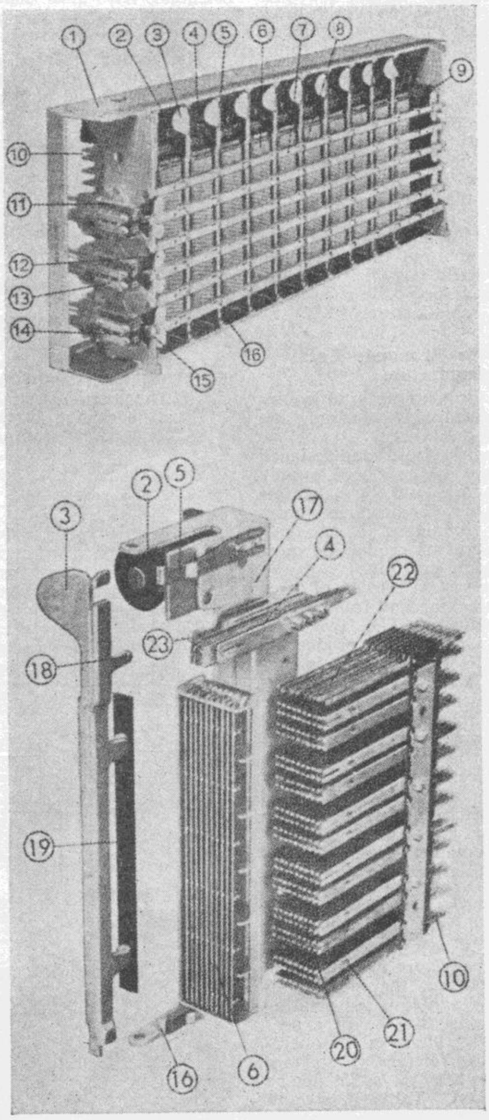


Fig. 9.—Crossbar Switch—Elements.

for junctions are governed only by the sensitivity of the pick-up and answer signal relays, and the use of sensitive reed relays for these functions will virtually remove the signalling limitation to junction resistance. Since with Registers the subscribers' dialled impulses are received and stored at the local branch exchange and do not require retransmission, the tolerance to impulse distortion can be increased considerably. The present dial-speed requirement of 9-11 i.p.s. can be relaxed to 7-22 i.p.s., thus considerably reducing, if not eliminating, dial maintenance and allowing a significant increase in subscribers' line resistance. The present resistance limit of 1,000 ohms is expected to increase to about 1,800 ohms which, as in the case of the junction limit, will permit an appreciable increase in the present transmission standard. These two relaxations in resistance limit will allow significant savings to be effected in our future external plant investment which, as mentioned above, comprises 70 per cent. of the local network investment.

The preceding discussion has centred on the technical facilities which must be met by the switching equipment. Of equal importance in a telecommunications network is that the equipment may be economic to purchase, install and maintain. In addition, in the Australian network it is important to ensure that to a maximum extent possible the equipment standardised should be capable of economic local manufacture.

Suitability for Economic Local Manufacture

In assessing the suitability of equipment for manufacture, two factors were considered important:—

(i) The equipment must be so designed that it can be produced simply and advantage can be taken of the latest developments in manufacturing techniques.

(i) The shop cost of production must be as low as possible.

Any telephone system consists of three main elements: racking and frameworks, relays, and switches. The two first elements are a common production problem no matter which system is considered and, in fact, the two Australian telephone equipment manufacturers have been producing relays and racking for the Department since the Second World War. However, by adopting crossbar there was a chance to simplify considerably the switch production problems. The crossbar switch consists essentially of a rectangular array of relays and springsets. The complete switch consists of a series of similar sub-assemblies (see Fig. 9) and at no stage are critical adjustments required during manufacture or assembly. The simple production and assembly requirements of the switch lend themselves to automatic methods. In contrast, the motor uniselector, which is a high-speed rotating mechanism, requires the use of expensive assembly jigs. Many of the operations involve close tolerancing and are of such a nature that they could not be readily automatised. Table II gives a brief comparison of the manufacturing requirements of the two switch types.

TABLE II.
Comparison of Switch Production Requirements

Date	10/20 Crossbar switches	200 Outlet motor uniselector
No. of piece parts	49 of which 13 are used in relays	135
Processes	Mostly presstools and stamping operations	Presstools and stampings for the banks, wipers and frame. Machine tools for the motor and gears.
Assembly	Rectangular non-critical assemblies	Careful jiggings and concentricity and bank alignment tests
Testing	Simple relay operations with no close tolerances	Close tolerances with critical speed requirements

The second essential consideration is that the cost of production of the switching system should be a minimum. It is possible to assess the likely relative costs of production of two switching systems when the following factors are realised:—

(i) The labour cost represents 75 to 80 per cent of the total costs for all types of electromechanical switching systems.

(ii) The number of control relays in a switching system does not vary significantly, from between 5 and 6 relays per line. This is independent of the type of control and applies equally to common control and step-by-step exchanges.

(iii) The main material component in an exchange is the speech path connection equipment or the crosspoints which, in assemblies, comprise the switches.

It follows from the above considerations that the exchange with the smallest amount of material in it will be the cheapest to produce and, further, the exchange using the fewest crosspoints or speech connections to achieve the required standard of service will possess the least material.

A study of this question of minimum crosspoint requirements shows that the number of crosspoints per subscriber's line can be made a minimum using crossbar switches in link-trunked arrangements. This is evident from the following simple example. Consider an exchange requiring 100 inlets and 100 outlets, and no congestion. There are three possible ways of achieving this result. Fig. 10 (a) shows the simplest

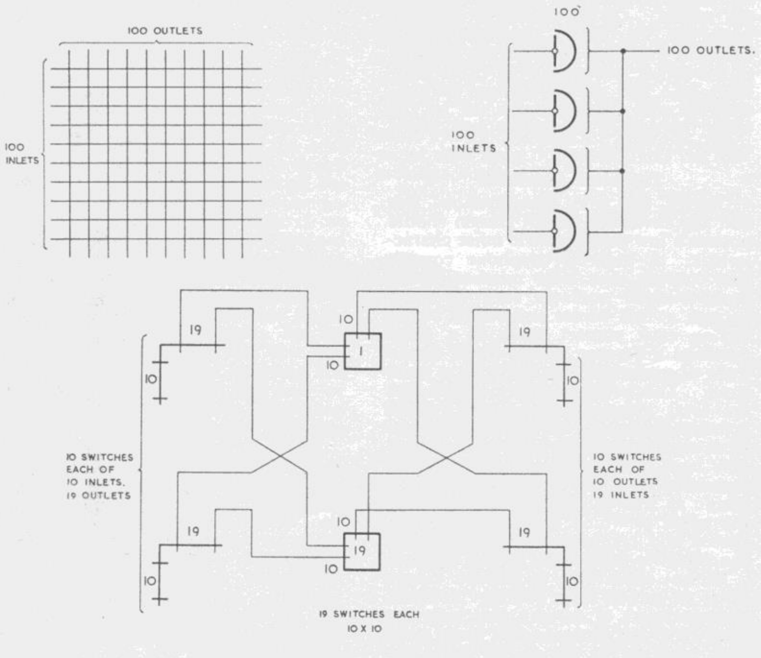


Fig. 10.—Trunking Principles.

arrangement, a single crossbar switch possessing 100 inlets and 100 outlets or 10,000 crosspoints. Fig. 10 (b) shows the same exchange using 100 outlet motor uniselectors or bimotional switches. 100 such switches are required utilising a total of 10,000 crosspoints. Both the above examples are cases of direct trunking, in which the free outlet from the switch is seized without first ensuring that at the next switching stage the associated inlet will itself have access to a free outlet. Fig. 10 (c) shows a link-trunked arrangement of crossbar switches so arranged as to provide the complete access with no congestion but using 5,700 crosspoints. In this switching stage the inlet is not connected to a link from the first switch until a complete path through the three switches has been tested and reserved for the connection. Crossbar switches may be arranged in linked arrays of two or three stages similar to that shown to provide any required availability. Clos showed that in this way an exchange could be trunked using the minimum possible number of crosspoints and that, from cases similar to the no-congestion example quoted above, exchanges having fixed standards of congestion can be derived. Finally, Clos demonstrated that a 10/20 crossbar switch is close to the ideal practical size for economic link-trunked arrays. Table II shows the relative number of crosspoints and relays per line for comparable exchanges using various switches for speech path provision.

TABLE III.

Exchange type	Crosspoints/line	Relays/line (approx.)
10/20 Link-trunked crossbar	20.0	6.0
22/52 Link-trunked crossbar	29.0	6.0
100 Outlet motor uniselector	65.0	6.0
200 Outlet motor uniselector	84.0	6.0

It can be seen, therefore, that the most suitable system from a manufacturing viewpoint would be a crossbar system with a 10/20 switch used in link-trunked arrangements.

Economic Installation and Maintenance

It follows from the above arguments that the system containing the least material should be the easiest to install. This, in practice, is proving to be the case. The three crossbar exchanges so far installed in Australia have each averaged between 5-7 hours/line for the exchange equipment compared with an equipment installation time of about 15 hours/line inclusive for a bimotional exchange. Bearing in mind that the three crossbar exchanges installed have been "first in" installations, the installation time could be expected to reduce further as familiarity with the equipment is gained.

An important cost in a telecommunications network is the maintenance charge for the exchange equipment. Crossbar equipment has the most favourable maintenance performance of any electromechanical switching plant, due mainly to the simple relay-like nature of the switch and, hence, the elimination of mechanical adjustments and the need for lubrication of moving parts. The only adjustments remaining are those associated with relays. A major problem is designing bimotional and motor uniselector switching systems is the integration of the relay circuitry with the operating tolerances of the mechanisms and motors, respectively. The result has always been a large proportion of marginal relays subject to close timing tolerances in the circuitry of these systems. With crossbar, the circuitry consists of simple logical blocks utilising for the most part "donkey" type relays.

Surveys of relative maintenance effort for various systems have been conducted in all countries, and Table IV is a summary of the general findings.

TABLE IV.

Equipment type	Staff per 1000 lines
Crossbar	0.1-0.3
British motor switch	0.4-0.5
German motor switch	0.5
SE.50 and 2000 type Bimotional switches	1.0-1.4

Future Developments

It is now possible to construct fully-electronic telephone exchanges, but the present rate of component development indicates that such exchanges are unlikely to be economic for some 10-15 years. However, it is clear at this stage that any exchange equipment purchased must be suitable for adaptation to electronic switching plant.

The main advantage of electronic control equipment is its speed of operation compared with relays. Therefore, to benefit from electronics, the switching medium must be capable of fast operation and overall simultaneous control from a single common equipment.

Conclusion

Taking all the above arguments together it becomes clear that the most desirable switching system for use in the Australian network is a link-trunked crossbar system, which has been fully developed and tried in service for local, rural and trunk transit applications, and has worked successfully with step-by-step networks. Of the systems on offer, the L. M. Ericsson crossbar equipment was chosen as most nearly fulfilling these requirements. This system, which uses 10/20 crossbar switches and link trunking, has been developed and proved in service in all applications and with a variety of other types of plant including step-by-step equipment. The next part of this paper will survey the origins of Crossbar Switching Equipment and describe briefly the system adopted for Australia.

PART II.—THE CROSSBAR SYSTEM

The crossbar switch was one of the earliest developments in automatic telephony. Betulander, a Swedish engineer, worked with the crossbar principle of switching in the early part of the century and, as a result, in 1912 he took out a patent for the first crossbar switch. The diagram in the patent application is shown in Fig. 11.

At the same time, development was in progress in the United States of America

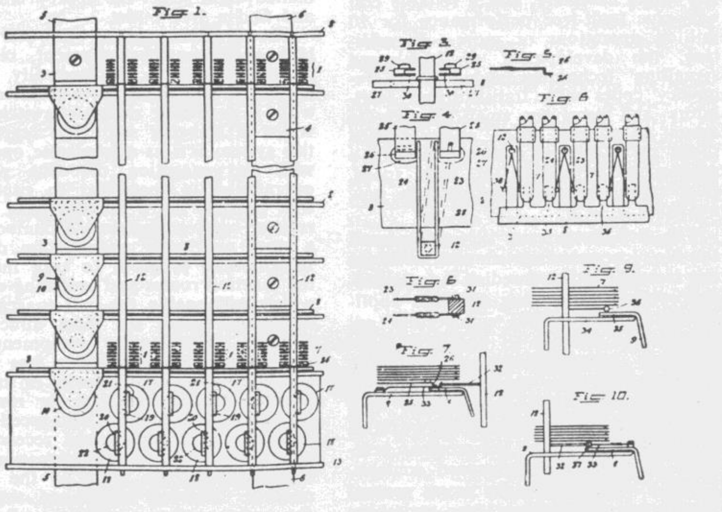


Fig. 11.—The Betulander Crossbar Patent.

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along similar lines. In May, 1913, Reynolds of the Western Electric Company patented a selector with relay contacts actuated by a system of crossing bars which produced a direct and instantaneous connection between a series of contacts. The Reynolds switch did not arouse great interest, due primarily to the large capital investment required for its development and manufacture. The selector was rather complicated and possibly too expensive to manufacture with the facilities available at that time. However, Betulander's crossbar principle was used to produce a relay switching system and the Relay Automatic Telephone Company acquired this system and installed several all-relay exchanges in the 1914-1920 period. However, these crossbar switches and the relay system were at this time too expensive when compared with the Strowger system based on a switch first patented in 1891 by Almon Strowger of Kansas City, and referred to at the beginning of this paper (see Fig. 1).

The main reason that these crossbar switches proved too expensive in exchanges at this time was that the common controls, on which a crossbar exchange relies, were not sufficiently fast in operation or reliable in service. Relay design and manufacture was in the early stages and single contacts were still used with little, if any, spark quenching. The wide operating tolerances, relatively slow speed of operation and the use of separate impulsing relays for each selector, were simplifying the conditions which resulted in the extensive use of the Strowger switch for early telephone exchanges.

It was not until about 1936 that technical developments in the field of relay manufacture enabled the designers to introduce an economic crossbar switching system. This development of the relay and other switching components has accelerated since the Second World War until today a relay with twin contacts of special alloy, copper-silver or palladium-silver, with adequate quenching where necessary, and a reliable coil will give fault-free performance for 10 million operations or more. In addition, the development of high-speed signalling techniques using voice-frequency codes with transistorised oscillators and receivers small enough to mount in a relay space, allows dialled digits to be passed from a store in a register to a marker, at high speed. High-speed common controls are now available.

The Bell System in 1936 introduced the No. 1 crossbar system and, at about the same time, the Swedish Administration was experimenting with the application of crossbar to small rural exchanges as well as to larger city exchanges. From this second beginning there has been an increasing tendency on the part of manufacturers and administrations throughout the world to take full advantage of the crossbar principle with modern high-speed controls. Table V demonstrates the recent general trend towards crossbar type switching by some leading manufacturers.

TABLE V

Manufacturer	Crossbar system	Previous systems
A.T.E. Liverpool, England	5004 5005A/B (Under development)	Strowger, 2000 type, SE.50 Siemens' motor uniselector (step-by-step)
Bell Telephone Manufacturing Co., Belgium	8B Crossbar and Pentaconta	8A, Crossbar 7 series Rotary Systems (Register controlled)
C.G.C.T. and L.M.T., France	Pentaconta crossbar	R6 and Standard Rotary Systems (register controlled)
L. M. Ericsson, Sweden	ARF 102 ARF (Swedish PTT) ARM 20/50 ARK 50 (In production)	ARF 101, ARF 50/51 ARF 30/50 Crossbar 5000 line system XY System (register controlled)
Mix & Genest, Germany	H.K.S. crossbar	Strowger and German motor uniselector
U.S.S.R.	Unnamed crossbar	500-line system and possibly Strowger
Siemens & Halske, Germany	ESK relay crossbar (Under development)	Strowger E.M.D. (step-by-step and register controlled)
Western Electric, U.S.A.	Bell Nos. 4A and 5 (In production for Bell Co. only)	Bell Crossbar System 1, 1A, 2, 2A and 4. Panel-Rotary, 100-outlet Strowger (register controlled)

A Comparison: Crossbar with Step-by-Step

As mentioned in Part I, the basic element in our present switching system is the bimotional selector. This switch steps vertically under the control of impulses received by the vertical magnet and then searches horizontally for a free outlet on the particular route associated with the level chosen. Thus, each switch receives one of the dialled digits and directs the call one step further towards its destination. Each switch has associated with it sufficient control equipment to recognise the dialled digit, select the appropriate level and find a free outlet.

The crossbar system, however, uses high-speed control equipment, registers and translators located centrally in the exchange, and these are associated only with a particular crossbar switch only whilst it is being set. The register in this system acts as a telephone operator, with the exception that the register operates at a speed far in excess of that possible by a human being. The register receives the dialled number into a store and, after examination of this information, proceeds to take into use the junction routes and switching centres which will enable the call to reach its destination using the most direct free circuits. The register equipment may test several routes to find a free circuit and, during the establishment of the call, it refers to the translator for route information and calls in high-speed voice frequency transmitters and receivers to pass the digital information to exchanges on the route to the called number. Having established the call, the register releases and is available to set another connection.

The application of the principle of common register control is possible only because of the high operating speed of the crossbar switch and the associated techniques of multi-voice-frequency high-speed signalling and high-speed register translator operator. A system of this type enables efficient use to be made of the existing switching and line plant. Register operation provides opportunities to take maximum advantage of flexibility in the use of junctions in the network and in the allocation of numbers to subscribers. With the Australian step-by-step system the junction routes used for a particular call are determined by the digits dialled, whereas, with the register crossbar system using suitable translations, the most direct free route can be used, and this may vary depending on the amount of traffic flowing in the network and its direction at any time of day. Thus, the junctions in the city business centre, which with the step-by-step system lie idle at night, may be used for residential traffic when register-controlled crossbar is introduced. With our step-by-step system, blocks of subscribers' numbers are allocated on a regional basis and, since subscribers' development is not uniform over the network, there is a shortage of subscribers' numbers in some areas whilst other areas have numbers to spare. With register crossbar equipment the allocation of numbers to subscribers in particular areas is far more flexible and number saturation in one area can be readily relieved.

The Crossbar Switch

The crossbar switch or selector, as the name implies, consists of a series of vertical bars or bridges and another series of horizontal bars. Fig. 7 shows a range of crossbar switches of various sizes.

These switches differ from the bimotional selector since they are not capable of setting up a connection without the assistance of an external control circuit. This control circuit receives the dialled digits and decides which inlet must be connected to a given outlet and then operates the corresponding horizontal or vertical magnets to close the relay contacts at the required intersection. Fig. 9 shows a crossbar switch of the type used by the A.P.O., and an enlarged and exploded picture of a typical bridge or vertical inlet.

The switch in Fig. 9 has 10 inlets or 10 vertical bridges, and 20 outlets, which are derived from the horizontal bars. Each bar will operate either to the top magnet or the bottom magnet associated with it thus lifting the selector fingers up or down. From five bars, therefore, 10 outlets are derived and the sixth bar operates as a wiper switching element in association with the other five to provide a total of 20 outlets.

Fig. 12 shows in detail the method of operation of the vertical and horizontal magnets to close a connection. To operate springset No. 6 in Fig. 12 the selecting magnet 6 tilts the selecting bar so that the selecting finger moves upwards over the flanges of the actuating spring and comes to rest against the projecting stop. Attached to the armature of the holding magnet is a vertical holding bar which normally moves into the recess of the actuating spring and, hence, does not operate the spring pile. However, when a selecting finger is moved from its normal horizontal position by the operation of the selecting bar, the outer extremity of the finger bridges the recess in the actuating spring so that, when the holding bar is operated, it comes into contact with the operated selecting finger and operates the appropriate springset. The selecting finger is held between the holding bar and the actuating spring by the pressure exerted by the holding magnet. Since the selecting finger is flexible, the horizontal bar can restore to normal and be used to assist in the setting of another call level and the first connection under the control of the holding magnet.

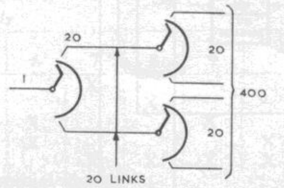

Fig. 13.—Link Trunking in Crossbar.

The Crossbar Switch as a Selector

Each vertical of the crossbar switch can be considered as a 20-outlet selector. Thus, a 10/20 crossbar switch consists of 10, 20-outlet selectors. Twenty outlets are not sufficient from a given selector stage to provide efficient trunking, and, in fact, this limitation to the number of outlets available is one of the disadvantages of bimotional switches. Crossbar switches can be arranged to provide for any number of inlets and outlets by a method known as link trunking. An illustration of this principle is given in Fig. 13, which shows how access is gained to 400 outlets from a given inlet using two ranks of selectors.

This principle of developing a selector stage from two partial stages of crossbar switches is used throughout the ARF exchange system, the type normally used in large city networks. The connections between the first and second partial stages are known as links, and the marker controlling the complete stage selects not only a free outlet but also a free link to connect the inlet to the required outlet. Hence, both partial stages are set simultaneously. Using this method of trunking, selector stages with any desired number of inlets and outlets can be constructed.

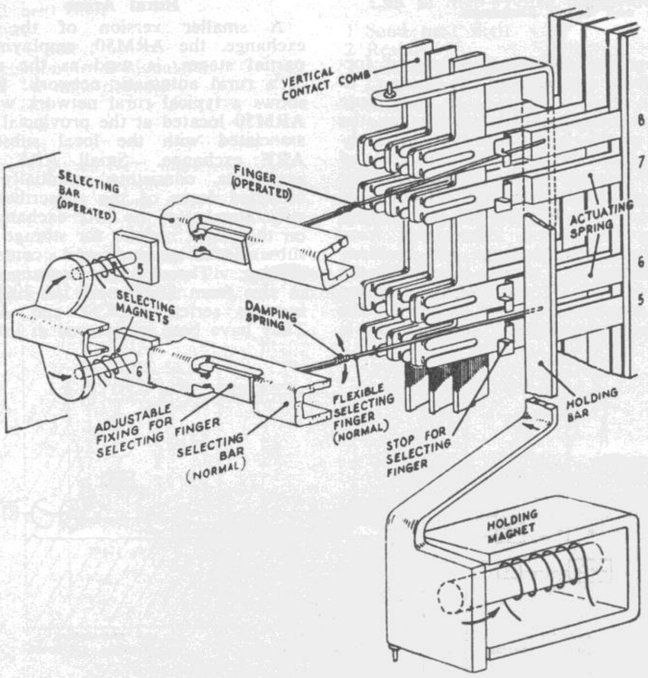

Fig. 12.—Operation Detail of Crossbar Switch.

Typical Crossbar City Exchange

The operation of a typical crossbar city branch exchange (ARF) is described below, with reference to the schematic diagram (Fig. 14).

Subscribers are trunked through two linefinder stages, SLA and SLB, in groups of 200 to the S.R. relay set. From this relay set access is gained through register access equipment to the local registers. The S.R. relay set provides transmitter battery feed and supervision for the calling subscriber. The group selector stage consists of two partial stages of crossbar switches arranged in units, each unit providing 80 inlets and 400 outlets. From this group selector stage, direct access is gained to the SLC and SLD stages of the subscriber's linefinder, final selector group. As well as these direct routes to 1000-line groups, a backbone route connects the group selector stage to the incoming group selector (GIV) and this route carries traffic not handled on the direct routes to the SL stage. The full SL stage provides access to 1000 subscribers. The SL stage is under the control of the SL marker (SLM) whilst the group selector or GV stage is controlled by the GV marker (CBM). Incoming calls from other exchanges pick-up Register I which controls the setting of the call through the GIV and SL stages. Outgoing calls from the GV stage may be routed either to other crossbar exchanges or to step-by-step exchanges.

When a subscriber removes his handset his line relay "LR" operates and indicates the call to the SL marker of the 1000-line group to which he belongs. The SL marker selects a free SR relay set and register and connects the calling subscriber through the SLA and SLB stages to this relay set and register. The marker is then released and the register transmits dial tone to the subscriber. The subscriber dials the wanted number, into the register. For a local call the register now controls the selection of the wanted subscriber.

First, the register seizes the GV marker associated with the GV or group selector unit to which the SR relay set has access. A code receiver KM in the GV marker receives from the register, by means of a high-speed signalling code, the digits required to select the correct outlet from the group selector stage. The GV marker connects the call through the required outlet on the SL

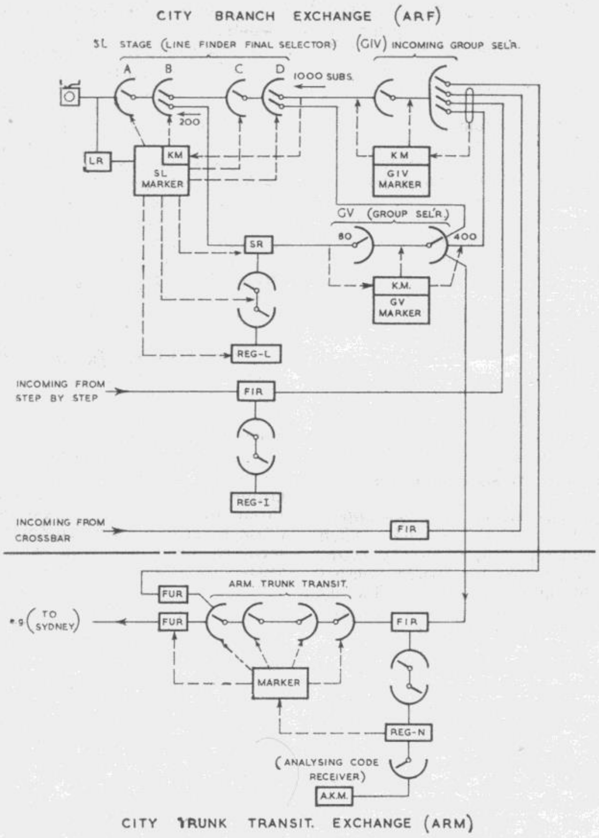

Fig. 14.—Crossbar City Branch Exchange and Trunk Exchange.

stage, and the SL marker is then seized. The GV marker releases as soon as it has completed the group selector connection. If there are no free outlets on the direct route to the 1000-line group required, the GV marker tests the route to the GIV stage, selects a free outlet and connects the call as before. The SL marker now calls for the three digits required to locate the subscriber in the particular 1000-line group already selected. These digits are also sent forward, using high-speed code, and are received by the receiver in the SL marker. The SL marker positions the four SL stages for the wanted subscriber and, having notified the register of the condition of the called subscriber, releases. The complete connection is held from the SR relay set which now transmits ringing current to the called subscriber and ring tone to the calling subscriber. At this stage, SR takes over control of the call, and the register releases. From this stage on, the supervision of the call under the control of the SR relay set is similar to the supervision in our present step-by-step exchanges.

For an outgoing call the GV marker selects the required outgoing route and identifies what type of signalling is required for the digits to be sent forward. For a route to a step-by-step exchange the digits would be sent forward from the register at 10 i.p.s. to position the selectors. If the route was to another crossbar exchange the digits would be transmitted in high-speed code direct to the code receiver of the GV marker at the distant crossbar exchange. Incoming calls from step exchanges seize Register I. This register receives the digital information from the step-by-step exchange and positions the selectors in a similar manner to the local register. If the call is incoming from another crossbar exchange, the multi-frequency coded information is taken into the code receiver (KM) of the GIV marker direct, and the call is completed in a similar manner to a local call.

Trunk Exchange

If the subscriber requires to call a destination outside the local network, for example a Melbourne subscriber calling Sydney, on receipt of the code for Sydney, "02", the Register L initiates action to connect the subscriber to a network register, Register N, at the trunk exchange. The trunk exchange equipment (coded ARM) consists of a selector stage built, according to requirements, of either two or four partial stages of switches, and controlled by common markets, registers and analysing code receivers. These trunk exchanges can be expanded in units of 200 lines up to a total capacity of 4000 trunks in and out.

The Register L proceeds to transfer the digital information into the Register N at high speed, and Register N assumes control of the call. The analysing code receiver (AKM) is called in to determine the charge rate to be applied, and when the called subscriber answers the receipt of the answer signal in the FIR-U causes meter pulses to be applied to the line at the rate appropriate to the call distance and charge. The routing of the call is controlled through the necessary transit switching stages by Register N. At each transit point the local code receiver calls for sufficient digits to enable the most direct free circuit to be taken into use as the next link in the connection. Having completed the selection in the transit exchange, the transit marker releases and the Register N talks direct to the next transit code receiver in the call.

Rural Areas

A smaller version of the ARM exchange, the ARM50, employing two partial stages, is used as the nucleus of a rural automatic network. Fig. 15 shows a typical rural network with the ARM50 located at the provincial centre associated with the local subscribers' **ARF exchange.** Small ARK (rural) exchanges, consisting essentially of a modified form of the subscribers' line stage element of the ARF exchange, rely on the ARM register for storage of the subscriber's number and control of routing. These ARK exchanges vary in size from 30-90 and 100-2000 lines in two series, ARK51 and ARK52. They have been engineered as unit type

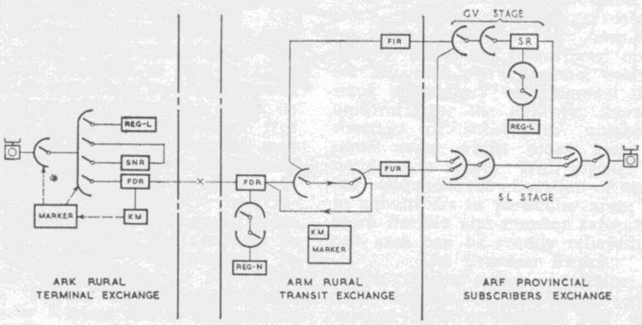

Fig. 15.—Crossbar Rural Network.

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equipments in cabinets, and, as such, can be readily installed and moved when required. In spite of careful planning, it is often found that in areas where these exchanges are required initially, unforeseeable expansion occurs and the telephone facilities may need to be replaced by city branch exchange type equipment.

When the subscriber lifts his handset a junction is seized to the ARM exchange and dial tone returned from the register. The dialled digits are stored in Register N and, if the call is outgoing, the connection is established through the ARM exchange and on to the destination. However, for a local call the register returns instructions at high speed to the marker in the ARK exchange and the call is established on a local link, the junction being released. If all junctions are busy or out of service due to fault or calamity, the call is intercepted by an emergency local register in the ARK which will complete local calls only.

TABLE VI.
Allocation of Frequencies and Codes for Forward and Backward Signals between Registers.

Forward Signals

	Digit	1	2	3	4	5	6	7	8	9	0
1380	0	X	X		X			X			
1500	1	X		X		X			X		
1620	2		X	X			X			X	
1740	4				X	X	X				X
1860	7							X	X	X	X
1980	10	Used with above for 5 special signals									

Backward Signals
Frequencies: 1140, 1020, 780, 660

A SERIES

1 Send next digit
2 Restart
3 End of Selection
(Transition to B signals)
4 5 digits) MFC terminal
5 6 ") Transition to
6 7 ") 2A signals
7 5 digits)
8 6 ") SxS terminal
9 7 ") Transition to
10 Number)
length) 3A signals
unknown

B SERIES

1 Idle sub.
2 Busy sub.
3 No throwout.
4 Congestion
5 Idle sub., non-metering
6 Interception service and malicious call

2A SERIES
Call to Crossbar Subscribers

1 Send next digit
2 Restart
3 End of Selection
(Transition to B signals)
4 Send 1st digit decadic
5 " 2nd " "
6 " 3rd " "
6 " 3rd " "
7 Waiting place, Next digit
8 " " , Restart
9 " " , Same digit
10 " " , Previous digit

3A SERIES
Call to Step-by-Step Subscribers

1 Send next digit
2 Restart
3 End of Selection
(Transition to B signals)
4 Send Previous Digit
5 Send 1st digit decadic
6 " 2nd " "
7 " 3rd " "
8 " 4th " "
9 " 5th " "
10 " 6th " "

Congestion is always given as A3 (or 2A3, 3A3) + 1B4.
Waiting place signal is only given once in a call. If the signals 7-10 are received once more by the register, they are interpreted as 3A7-10.

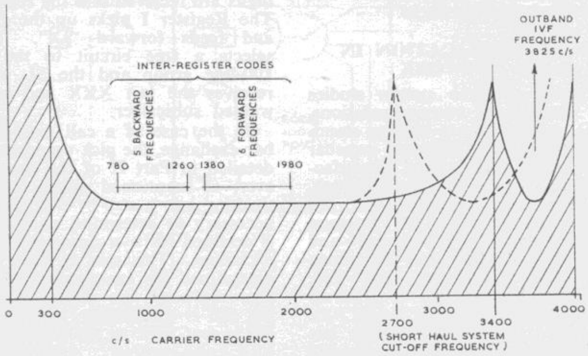

Fig. 16.—Signalling Frequencies.

Signalling

In telephony, signalling is the general term applied to the process of establishing, supervising and, when necessary, disconnecting a connection between two subscribers. There are two broad categories of signals, termed information and line signals. The information signals are the digits the caller dials to specify the party to whom he wishes to be connected. The line signals are those signals necessary to seize a junction to guard it against intrusion until the call is clear, to signal when the called party answers so that the call may be charged and to clear the connection after the conversation.

With a register-controlled system the information is stored in the register and passed to other registers or code receivers as required. The information signalling system is separate from the line signalling system, the former being associated with the registers and code receivers whilst the latter is associated directly and permanently with the junction or trunk line.

In the present step-by-step network the various trains of impulses from the subscriber's dial are used as they arrive, to position the selectors in the connection, each impulse train extending the call one step further towards its destination. By this means, the call is extended to the distant subscriber as soon as the last impulse train has left the caller's dial and positioned the final selector. Ring is fed to the called subscriber almost immediately and the caller receives ring tone.

With a register system, however, the wanted number is fed into the register and the system does not start selecting a route until three or four digits have been received. This is an advantage since the more information possessed before routing commences, the more intelligent can be the routing decision or, in other words the cheaper can be the route chosen. However, since delay has occurred, the switching and signalling system must switch and signal faster than the subscriber candial in an attempt to make up the lost time. The information used at the various stages for routing the call consists of the digits the subscriber has dialled. The digital information is held in the originating register and transferred as required to subsequent registers and code receivers using a high-speed coded system of signals. The code to be adopted for Australia is designed for error checking, each digit being represented by two frequencies, and receipt of any other number of frequencies is recognised as a false signal. The chance of speech imitation or crosstalk being recognised as a signal is thus virtually eliminated. These frequencies must be so located in the speech band that they do not interfere with the frequencies used for line or supervisory signals. Fig. 16 shows the channel frequency spectrum and the information signalling. Table VI sets out the codes for forward and backward signalling between registers.

The backward or reverse signals are used to call forward the next digit required by the code receiver, A, 2A and 3A series, to indicate the class of the called subscriber's line to the outgoing exchange, 1B series, so that busy or ring tone can be fed to the calling subscriber, and to indicate to the controlling register whether the call is to a crossbar or a step-by-step subscriber, A series. This last type of signal is necessary for two reasons:—

(i) If the call is to the step-by-step network, routing must be commenced as soon as possible because subsequent digits must be pulsed into the step-by-step network at 10 i.p.s. and full advantage cannot be taken of the fast signalling code. In the case of a call to a crossbar subscriber, the routing and switching may be sufficiently fast on a particular route (say a direct route) to cause a "waiting place" signal to be used. In this case the route is not seized until all digits have arrived in the store. If the route were seized earlier than this, the common code receiver equipment would be held for an inordinately long time waiting on the dialled digits from the subscriber.

(ii) For calls to crossbar destinations the register releases after an end-of-selection signal has been received from the distant code receiver to signify that routing is complete. However, in the case of step-by-step destined calls, no such end-of-selection signal is possible and, consequently, the register must release after it is satisfied that all digits required have been sent on. Therefore, a number length signal is transmitted to the register to indicate the number of digits required for the particular code dialled. Unfortunately, in our networks numbers of all lengths from 3 to 7 digits are in use spread randomly through the number range. Where the number length cannot be determined from the first four digits of the code dialled, the "don't know" signal is used and the register releases a short period after clearing its store. Finally, the register is also designed to release four seconds after it has cleared its store if no further digits arrive.

A description of the use of these backward signals is given in the section dealing with application in metropolitan networks.

The line signalling systems required in a crossbar network are required to perform only the supervision of the links between exchanges. The code of signals used is given below:—

Forward	*Reserve*
Seizure	Answer
Clear Forward	Clear Back
	Release Guard
	Blocking
	Meter pulses (when required on end links)

These signals can be achieved using D.C. loop signalling, utilising the two conditions, loop and open circuit. On derived circuits, a single voice-frequency can be employed using a pulse length code, 50 milliseconds pulse for seizure, 150 milliseconds pulse for answer, and so on. An alternative recently introduced is the utilisation of a channel just above the speech channel but below the carrier frequency, to carry a single frequency signal. The frequencies commonly used are 3825 or 3850 c.p.s. The advantage of this system is that the signals are isolated from the speech channel and, in consequence, simple loop and open-circuit conditions can be simulated. In addition, meter pulses can be sent back during conversation without interfering with speech.

Reference was made earlier to the Compelled Sequence method of signal transmission. This method is preferred for both outband line signalling and for inter-register signalling. The scheme is one in which the forward signal is sent until an acknowledgment is received at the outgoing end. This acknowledgment cuts off the forward signal and the break in turn cuts off the acknowledging signal. Further, the acknowledge signal in the inter-register case is used to indicate to the originating register the next signal required. This compelled sequence method is proof against most transient interruptions likely to occur on open-wire routes and transmission systems, and, due to the one-at-a-time flexibility of the procedure, only the information required at each centre is sent forward.

The simplified requirements imposed on the line-signalling equipment have resulted in an increase being possible in the allowable D.C. resistance limit of junction cables. The previous restriction imposed by the requirement to minimise impulse distortion has been removed in a crossbar network and the limiting condition is the ability of the receiver relay in the outgoing repeater to hold over the answer reversal. The allowable limit has been increased from 1,200 to nearly 4,000 ohms. Similarly, with register control, the pulses from the subscriber's dial only require to be identified by the register store receiving relays. The subscriber's line resistance can consequently be increased from 1,000 to 1,800 ohms. Both these relaxations will allow considerable savings to be achieved in the subscriber's and junction reticulation networks.

PART III.—APPLICATION IN A.P.O. NETWORK

As a result of these system studies and the consequent recommendations, the A.P.O. decided late in 1959 to standardise on the L. M. Ericsson crossbar equipment for supply, local manufacture and application in the network. An agreement was negotiated between the Department, the L. M. Ericsson Company, Standard Telephones and Cables Pty. Ltd. (Sydney) and Telephone and Electrical Industries Pty. Ltd. (Sydney) whereby the two local firms would manufacture crossbar for A.P.O. requirements. Considerable effort has since been directed towards the planning and programming for the initial supplies of equipment, both purchased direct from Sweden and manufactured locally, to ensure that the initial inter-working problems have been allowed for and to enable smooth introduction of the initial deliveries to commence in the 1961-62 financial year. The following sections indicate briefly the way in which the equipment will be integrated into the network.

Metropolitan Networks

There are three broad categories into which the initial crossbar installations can be grouped in city networks. New exchanges naturally will be installed exclusively with crossbar equipment, and examples of these currently on order from L. M. Ericsson are: Haymarket, 1961-62, 8,000 lines, a central city exchange in the Sydney network; Flinders, central city exchange in the Adelaide network, 1961-62, 5,400 lines; Cooma, a provincial centre exchange, 2,000 lines. Already installed and cutover in September, 1960, is Toowoomba (Queensland), 6,300 lines, a provincial local exchange which, together with two small exchanges, Sefton (N.S.W.) and Templestowe (Victoria), represent the present working crossbar equipment in the network.

In the second category are the crossbar extensions to existing step-by-step branch exchanges. To allow extension of these exchanges with crossbar, it is planned in each case to close them off when the current 1,000-line unit is fully allotted and, using one digit of the six-digit exchange code, open up a seven-digit 10,000-line crossbar section. The block schematic trunking for such an exchange is shown in Fig. 17.

The six-digit step-by-step exchange in this example has 10,000 numbers with code 53, and level 1 has been expanded to seven digits to provide a fresh 10,000-line group with code 531, XXXX, leaving 9,000 numbers on the step-by-step exchange with codes 53,2-0,XXX. Consider the original step-by-step calls. The uniselector connects the subscriber to a 1st selector in the main exchange (see Fig. 2), and a call for 53,XXX arrives via the 1st and 2nd selectors to the 3rd selector. If the call is destined for the step-by-step exchange, it continues to the final selector. If the code is 531 an interworking register is seized from level 1 of the 3rd selector and the remaining digits are received into the register store. The Register I picks up the GIV stage and feeds forward "IX". The GIV selects a free circuit to the required 100-line group and the SL stage then receives the last XXX and selects the wanted subscriber.

In the case of a call from the crossbar exchange, the pick-up procedure is as detailed in Part II of the paper. However, as mentioned above, when interworking into a step-by-step network it is necessary to determine whether the call is destined for a crossbar or step-by-step exchange. This can, in most cases, be determined by examination of the first four digits of the dialled number. If the call is to crossbar, the signal A5 or A6 is sent back to the register from the IGV code receiver. After this, all signals passed back are in the 2B series

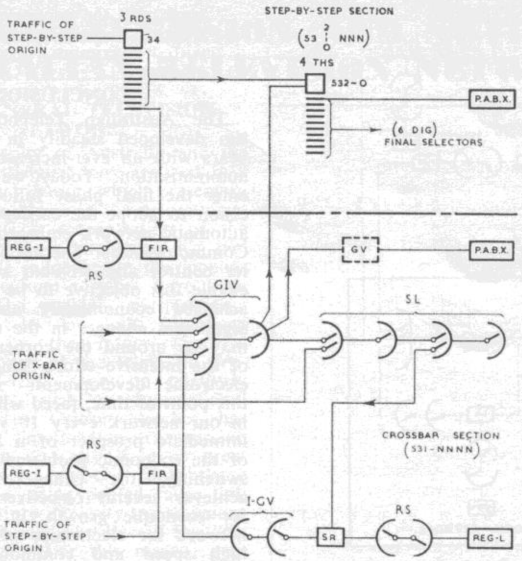

Fig. 17.—Extension of 6-Digit Step Exchange with 7-Digit Crossbar.

which has been designed for controlling a call through the step-by-step and crossbar network to a crossbar destination. Signals 2A, 5, and 7 are designed to allow for the case when the call is routed through a step-by-step switching stage. In this case the maximum flexibility is achieved if all digits are pulsed out decimally and another Register I is seized when the crossbar network is re-entered. For calls to step-by-step equipment, one of signals A7-10 is returned and the subsequent signal from the 3A series indicates from what digit the register must start when pulsing out into the network.

Incoming calls from the crossbar network arrive on the GIV and may be destined either for the crossbar or step exchanges. The first digit received will be the 3rd, and, if 1, the code receiver will call for the first X and route to the required 1,000-line group. If the digit is 2-0 the GIV will select a route to the appropriate rank of 4th selectors and send a revertive signal to the Register L to send the 4th and subsequent digits decimal.

The third application of crossbar equipment will be the introduction of the first selector stage and register, which are in effect the essential elements of the crossbar switching system, into step-by-step exchanges instead of or to replace D.S.Rs. (discriminating selector repeaters.) This requirement arises in one of two ways. Either on extension the D.S.Rs. or their earlier equivalent the S.S.Rs. (switching selector repeaters) are replaced, or a trombone trunked exchange is converted to a group selector branch by the introduction of a crossbar 1st group selector stage. A typical trunking diagram, showing the replacement of the D.S.R. with a crossbar group selector stage, is shown in Fig. 18. The D.S.R.

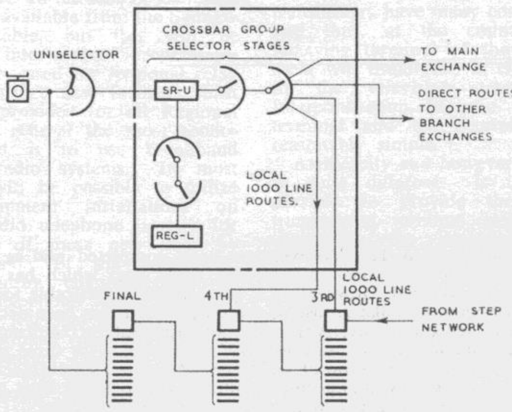

Fig. 18—Crossbar First Selector Stage in Step Exchange.

is used in some step-by-step branch exchanges to provide direct routes to other exchanges in the same main exchange area, that is, possessing the same first code digit. All other calls are routed via the main exchange first selectors. The crossbar GV stage places no limit on the code groups to which direct routes can be established and, thus, a large portion of the traffic load can be removed from the main exchange route. In addition, a direct route can be established from the GV stage to the trunk switching equipment to handle trunk traffic. This is not possible on the trunk code "O" using the present 2,000 type D.S.R.

Rural Networks

In the rural networks, the first requirement will be to minimize purchase of further R.A.X. equipment which cannot be readily integrated in the national numbering and switching scheme. For this reason, the initial bulk orders of equipment will contain a proportion of ARK country terminal exchange equipment. These small units, ranging in size from 30-2,000 lines, will cover a very large proportion of the requirements in country areas for automatic equipment, to take the place of the R.A.X. and the medium-sized manual exchanges. Where the exchange will grow beyond 1,500 lines in the 20-year period, or the proportion of local traffic is high, an ARF exchange would be considered, especially where the rate of growth is high.

The introduction of ARM transit equipment in country areas is also being planned to provide a core for the ARK exchange networks and to facilitate distance dialling.

Trunk Network

The present operator-controlled step-by-step trunk network is of basically different character from the step-by-step local networks for two reasons:—

(i) The number is open, or, in other words, the digits dialled by the operator to reach a certain location vary, depending on the location of the operator and the route she chooses to take. For example, a Perth operator calling Sydney via Adelaide may dial 80351, whereas an operator at Adelaide dials only 351. In the national numbering scheme subscribers or operators would always dial 02 for Sydney, no matter where in the Commonwealth they were and how they reached their destination.

(ii) The present method of signalling on long distance carrier telephone channels using 2VF has been designed especially for operator dialling, and the system would not be entirely suitable for use on a subscriber-dialled system with high-speed circuit seizure.

For these reasons, it is generally considered that the objective should be to retain this network as an entity and to build up in parallel a subscriber-dialled long-distance network linking progressively the local networks. The present network would continue to handle the traffic not catered for by subscriber-dialling facilities or to assist the subscribers requiring a telephonist to complete the call. The operators would

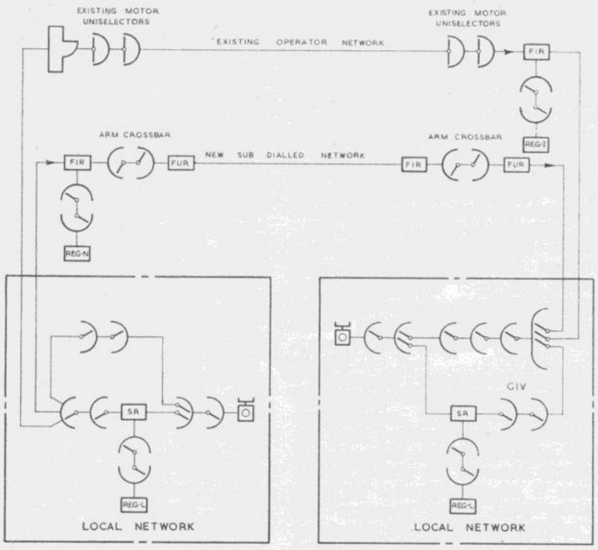

Fig. 19.—Development of Trunk Network with Crossbar.

have access into the subscriber network as shown in Fig. 19.

The first large-scale problem to be solved in the trunk network will be the provision for subscriber dialling out of the large capital city networks. This is becoming necessary in both Sydney and Melbourne, and will become important elsewhere to avoid further costly extensions to the manual trunk exchanges in these centres. To achieve S.T.D. from the large city networks, several additions and modifications to existing plant are necessary:

(i) The installation of a main ARM trunk transit exchange in the centre concerned. This installation would provide analysis for charge determination, routing and access-barring of subscribers who did not want their telephones used for long-distance dialled traffic.

(ii) The modification of existing meters in many exchanges to allow for multimetering.

(iii) The modification of repeater equipment to pass meter information back to the branch exchange from the central ARM transit.

Work is proceeding with the objective of solving the problem of meeting all three requirements. The resulting trunk transit exchanges will be the present-day equivalent of the 1940 Melbourne Trunk Exchange and the keystone on which the nation-wide S.T.D. network can be developed. This network will develop to fulfil two primary objectives:

(i) The progressive automatisation of the whole Australian network, and the consequent provision of a high-grade continuous automatic telephone service.

(ii) The steady reduction in manual operating, and consequent high costs, and the expansion of the network to meet demands for service with maximum economy and efficiency.

CONCLUSION

The Australian Telephone Network has developed steadily in the past 50 years with an ever-increasing degree of automatisation. Today, we are about to enter the final phase following the decision to adopt the concept of a single automatic network embracing the whole Commonwealth. The adoption of register control and crossbar switching will enable this objective to be progressively achieved economically and efficiently. Significant changes in the telephone art may be around the corner as a result of the intensive effort being invested in electronic development. However, at this point of time, faced with a doubling in our network every 10 years, and no immediate prospect of a firm solution of the economic problems of electronic switching, the change contemplated achieves several objectives. It allows for economic growth, it prepares the network for electronics which must be high speed and common control in nature, and it takes advantage of the latest engineered developments in the telephone switching art, developments which cannot be seriously threatened, on present information, for at least 10 years.

ACKNOWLEDGMENT

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‘And Now the Biography’: 150 Years of ‘Telegraph’ Todd

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Abstract: Sir Charles Todd is a seminal nineteenth-century figure who continues to fascinate popular writers and scholars alike, not least those working in modern telecommunications. A well-attended symposium, convened by Adelaide societies in August 2012, paid lengthy tribute to his wide-ranging achievements. In his own lifetime, ‘Telegraph’ Todd was celebrated for his achievement in planning and organising the construction of the Overland Telegraph Line from Adelaide to Darwin, linking Australia to the outside world. His personal intervention on the hazardous Northern Territory leg of the Overland Telegraph’s construction was hailed as decisive in the successful completion of one of the great engineering feats of its day. Yet Todd himself has remained a shadowy figure, eluding a series of biographers for more than a century after his death. This article concerning the genesis of Todd’s recent biography entitled *Behind the Legend: The Many Worlds of Charles Todd*, examines changing historical perspectives on Todd and his achievements. In particular, it identifies the increasing availability of biographical resources over time and reviews the challenges which biographers faced in bringing to life the career of a great pioneering Australian.

Keywords: Telecommunications, History, Innovation, Charles Todd.

Introduction

In his own lifetime, ‘Telegraph’ Todd was most celebrated for his achievement in planning and organising the construction of the Overland Telegraph Line (OTL) from Adelaide to Darwin, linking Australia to the outside world. His personal intervention on the hazardous Northern Territory leg of the Overland Telegraph’s construction, and his demonstrated capacity to overcome serious obstacles and flagging morale, were hailed as decisive in the successful completion of one of the great engineering feats of its day (Moyal 1984, p. 42). His rapid colonial recognition owed much to the heroic image which the colonial press subsequently projected of South Australia’s prominent civil servant. For modern telecommunication writers like K. T. Livingston (1997, p. 8), the OTL episode remains significant in the ‘public making’ of Todd, the colonial manager. It is on this basis that

Donald Lamberton, in his 2000 Charles Todd Oration, acknowledges Todd as 'a skilled networker, a great people person and a good strategist tuned to political events' (Lamberton 2001, p. 68).

In keeping with its biographical approach, this article overviews the extensive literature on Todd and the Overland Telegraph both during and after his lifetime. In the first instance, it shows how Todd's recognition owed something to other technologies like photography and newspaper illustration, before identifying the ways in which Todd was able to harness publicity during and after his 'great work'. In keeping with the fortunes of other great technological innovators, Todd's reputation has waxed and waned over time, while his remarkable service in the lead-up to federation has been too often written out of the national record. Yet, after his death in 1910, twentieth-century writers continued to mine the historical record, largely on the strength of Todd's own exemplary documentation, but also because collecting institutions have best preserved those records pertaining to his telegraphic work. Sustained in the professional literature for much of the twentieth-century, his reputation enjoyed a remarkable resurgence in the late twentieth century, when a combination of social and technological changes brought him once more to national prominence. Finally, in mapping this long personal trajectory, the article shows how interest in Todd's life and work continues to evolve into the twenty-first century.

This article concerning the genesis of Todd's recent biography entitled *Behind the Legend: The Many Worlds of Charles Todd* (Cryle 2017) examines changing historical perspectives on Todd and his achievements, including contributions on the subject to the *Australian Journal of Telecommunications and the Digital Economy*. In particular, it identifies the increasing availability of biographical resources over time and reviews the challenges which biographers faced in bringing to life the career of a great pioneering Australian.

The Making of a Colonial Icon

Todd's rapid recognition in the 1870s was aided by the rise of newspaper illustration in metropolitan weeklies such as the *Australasian* and *Town and Country Journal*, which contributed to the wide dissemination of photographs of his Northern Territory expedition. Although photographs could not be easily reproduced in colonial newspapers, even after the half tone process was introduced in the twentieth century, detailed illustrations could be produced using woodcuts, a technical process lasting several days, during which the engraver set out to reproduce an original image 'as a pattern of engraved lines on the woodblock' (Dowling 1999, p. 117).

This process of cultural transformation helped to transform colonial figures like Todd into heroes (Sebe 2009). The success of explorers in Australia was nevertheless ambivalent, constrained by the harsh climate and often by the assistance or aggression of their Aboriginal hosts. In the mid-colonial period, both Burke and Wills' and Leichhardt's transcontinental ambitions ended in tragedy, while John McDouall Stuart, repulsed by the Aborigines on at least one occasion, and desperately ill on his final return journey from northern Australia, achieved only a pyrrhic victory after his strenuous and repeated attempts. Yet it was the 'scientific legacy' of such explorers (Sebe 2009, p. 43), captured in Stuart's accurate maps and surveys of the interior, which provided an opportunity for Todd, allowing him to follow Stuart's tracks across the Australian continent when constructing the international telegraph link. Although explorers such as Stuart and Leichhardt ranked highest in colonial importance, Todd's rapid advance across central Australia with large numbers of workers, construction materials and supplies, constitutes a no less remarkable nineteenth-century achievement. For the establishment of the Overland Telegraph Line, in turn, opened the way for more extensive exploration of the Centre and the West, much of it undertaken by those who worked under Todd.

Todd as Publicist and Information Manager

Along with family letters and photos, newspapers provided Todd and his officers with valuable reading matter during their isolation at the Roper landing in the Northern Territory. Personal correspondence with Alice confirms that Todd was undertaking a more detailed reading of the press than simply following local happenings. He was at pains to request a wide cross section of newspapers, duly collected by family members and dispatched in a bag to him through the Adelaide Post Office (Todd, C. 1872). With the timely appearance of the *Illustrated Adelaide Post*, ahead of the illustrious *Australasian Sketcher* in Melbourne, Alice purchased the issue of 10 July 1872 and sent it on to Charles in the following month (Todd, A. 1872). It featured a series of northern scenes on the front page to whet local interest about the telegraph. At sixpence a copy, colonial and British pictorials were competitive with daily broadsheets, and proved just as effective as the attractive, but more expensive, landscape photographs taken by Captain Samuel Sweet, in replicating and publicising the visual iconography of the Roper River camp and the Overland Telegraph Line. Sweet accompanied Todd at a critical moment of the 1872 Northern Territory expedition during which, contrary to the advice of his ships' captains, Todd ascended the flooded Roper River and established a depot from which to supply stranded inland construction teams.

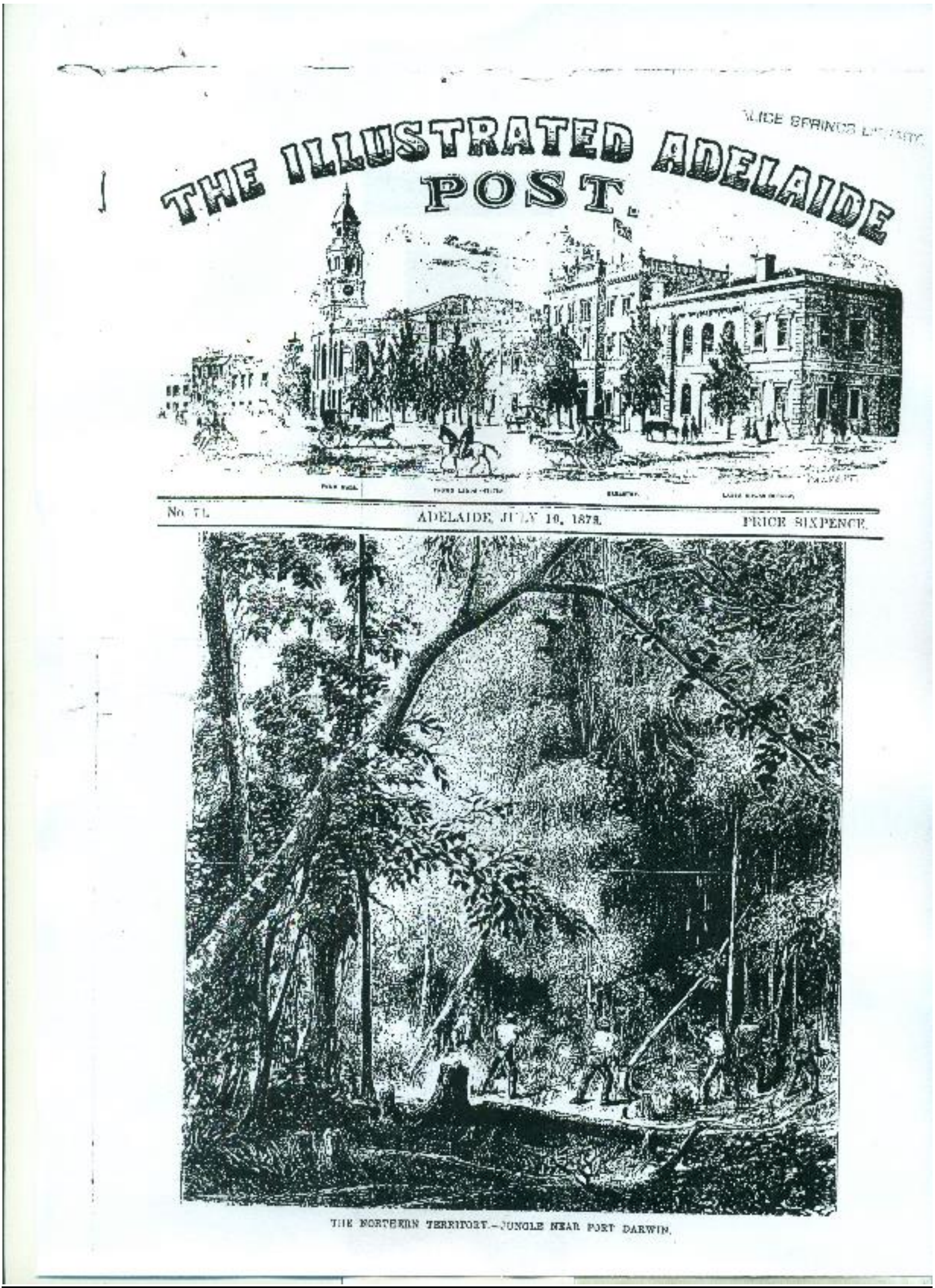


Figure 1. 'The Northern Territory — Jungle near Port Darwin', *The Illustrated Adelaide Post*, 10 July 1872

Within the Australian colonies, illustrated papers were quick to capitalise on the expectations surrounding Todd's northern achievements. In August 1872, the *Illustrated Australian News* led the way with a portrait of Todd, even before his successful return across inland Australia. By 1873, with the telegraphic link now open, the *Australasian Sketcher* (1873) circulated an illustration of Todd whom it asserted was now 'widely known beyond the limits of the colony for his zealous and able exertions on behalf of the Overland Telegraph'. Illustrated papers like the *Sketcher* favoured visual symbols of colonial progress, be they railways, streetscapes, or images of rural settlement (Dowling 1999, p. 121). In keeping with this preoccupation, the *Sketcher* published an illustration of the Alice Springs telegraph station before turning its attention to Todd's essential role. His epic telegraph, straddling the continent, exercised a dual fascination as an example of a modern technology established in an inhospitable rural environment.

By early 1873, news of Todd's success had reached the pages of the *Illustrated London News*, a title mentioned in Alice's and Charles' correspondence. Since 1842, the weekly *Illustrated London News* had pioneered the new art of visual journalism and become a model for colonial press imitators. The second page of its February article was given over entirely to illustrations, with landscape sketches of the Roper camp and telegraph vessels grouped around a larger woodcut reproduction of the iconic Todd photograph. While not simply a promotional piece about Todd, it confirmed his leadership role in the Overland Telegraph Line, in the first instance as the instigator, but primarily as the 'executor' whom 'neither the shipwreck of his stores, nor the difficulty of struggling across a flooded country could daunt' (*Illustrated London News*, 1873).

In the United Kingdom, as in Australia, the Todd legend was growing, in spite of opposition from Queensland critics and the carping of Patterson, Todd's northern overseer. Yet if Todd had been responsible for supplying this material from his own archive, as his correspondence suggests, he made no serious attempt to steal the limelight. As South Australia's Postmaster General, he belonged to the civil service, an occupation which, despite its significant historical contribution, has received little in the way of historical or popular recognition. Within this group, Todd would emerge, however, as a notable exception, adept at exploiting the telegraph's capacity for rapid communication between government and the press. An example of his willingness to keep the public informed, from the field as well as the office, was Todd's use of a pocket relay in central Australia to tap into the completed transcontinental line and acknowledge messages of congratulations from around Australia. Predictably, however, the intensity of newspaper coverage, extending as it did beyond South Australia, attracted its share of criticism, most notably at the hands of the *Sydney Morning Herald* (1872) and the Brisbane *Telegraph* (1872), which fuelled rumours about the impending failure of the new Line. It would take Todd considerable time to quell the doubts and envy of rivals and collaborators, through a mixture of public refutation and private correspondence.

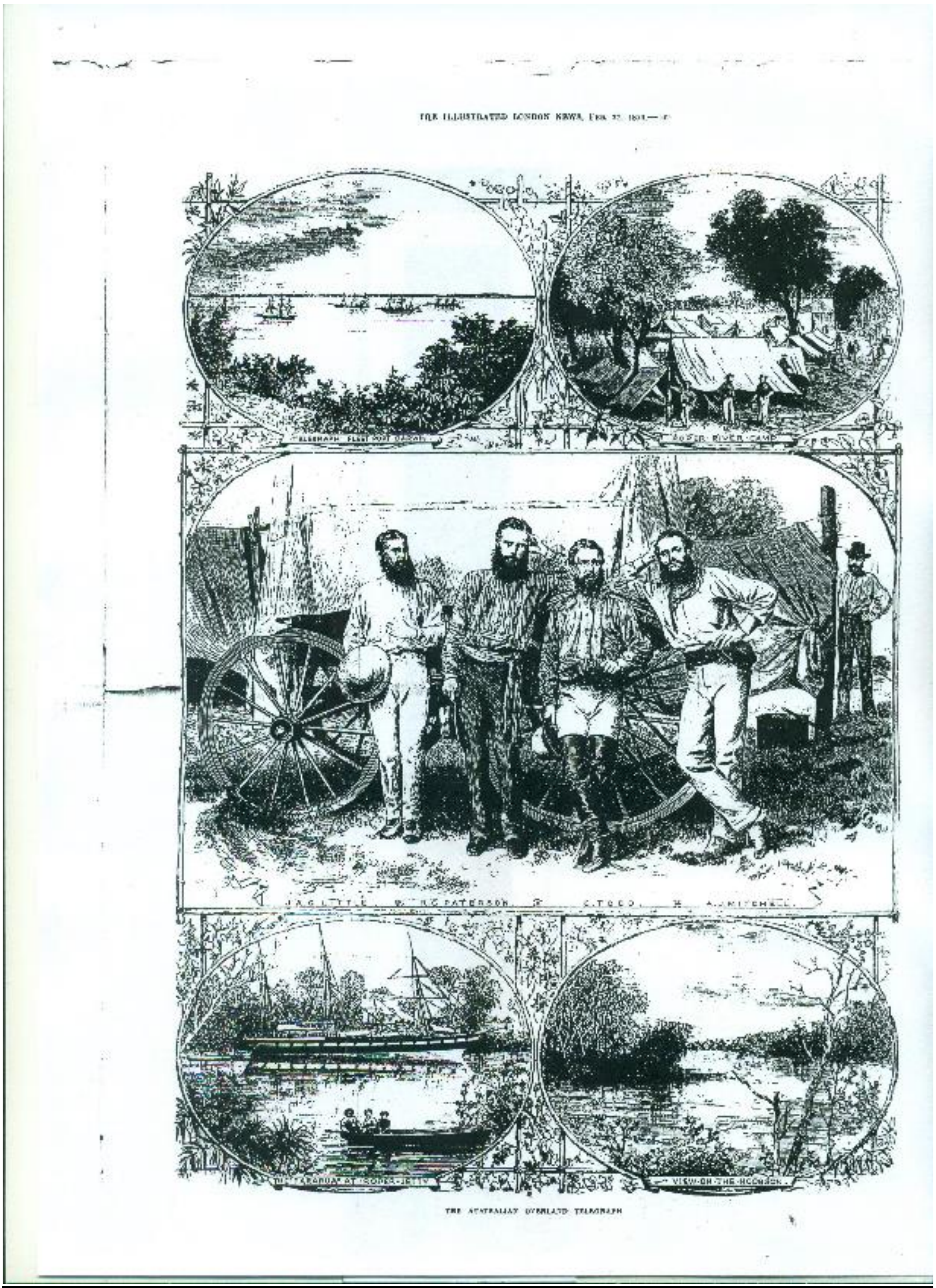


Figure 2. 'The Australian Overland Telegraph', The Illustrated London News, 22 Feb 1873, p. 169

Apart from his contribution to land exploration, Todd's propensity for timely report writing from the field sustained his growing popularity with the colonial public and would continue into the twentieth century. But in the short term, it was a growing interest in portraiture and photography to mark noteworthy occasions that would most benefit his cause. Samuel Sweet, destined to lose his commission after his vessel ran aground in the north, proved himself a better photographer than sea captain, taking what Todd described as 'splendid photos' of the fleet and the Roper landing, and, more importantly, what became *the* iconic photo of Todd's famous northern expedition. For this purpose, Sweet captured Todd and his officers — Patterson, Mitchell and Little — in 'regular bush rig', using a wagon behind them to create a studio effect. Todd, conscious that it was 'a unique moment in history', wrote excitedly to Alice in Adelaide, describing it as 'a very good picture of myself' adding that: 'I think you will like to have a glimpse of me as I appear here' (Todd, C. 1872). Sweet's image was designed to emphasise teamwork, despite the fact that Todd and Patterson were regularly at loggerheads over leadership of the relief expedition.

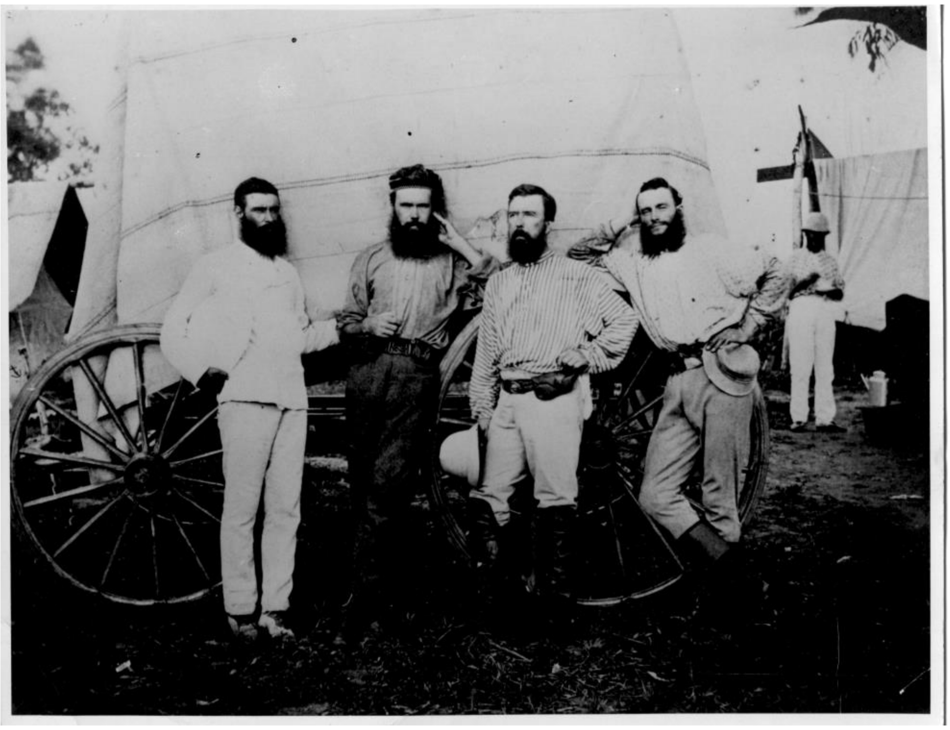
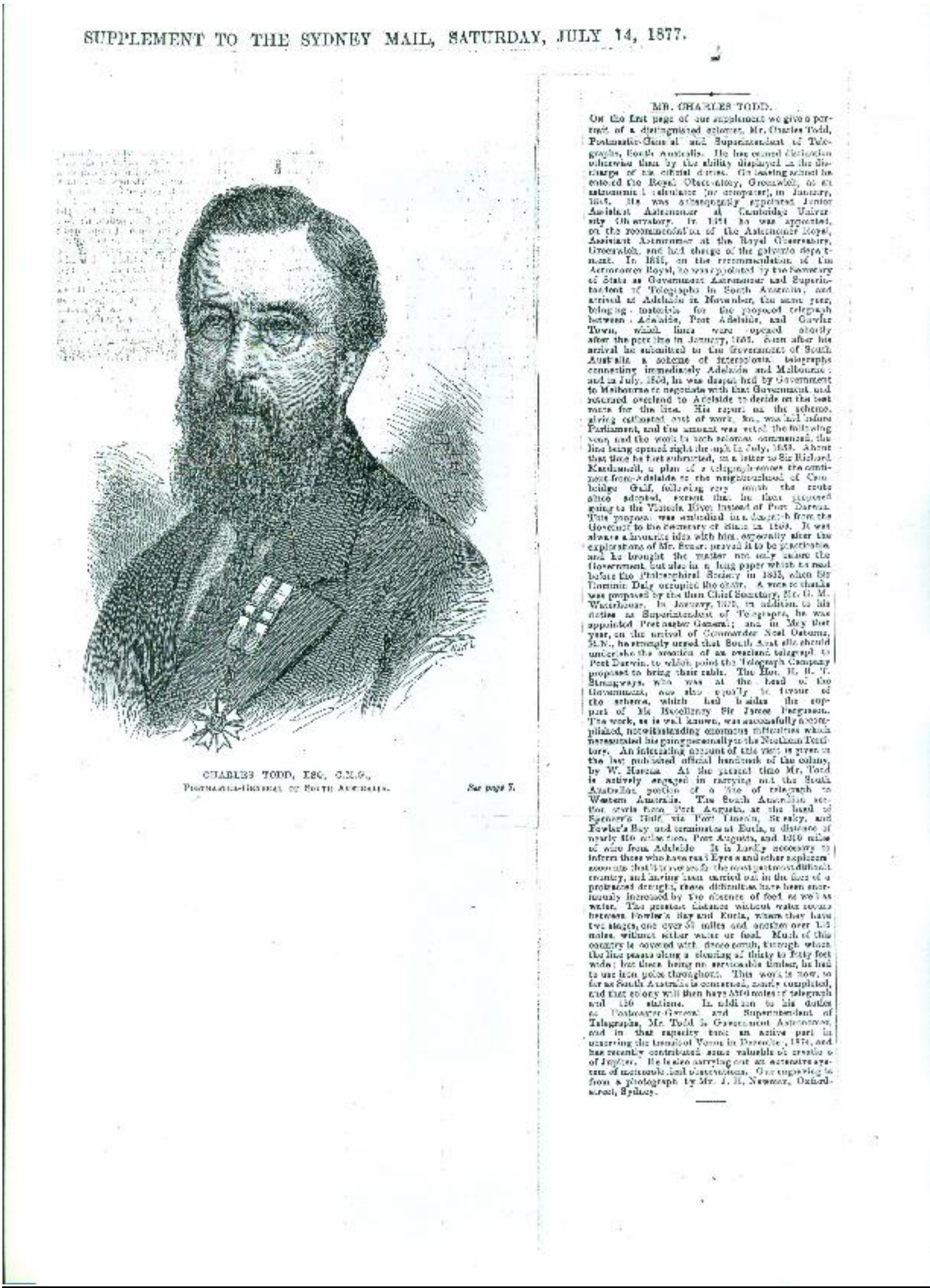


Figure 3. Charles Todd and the Overland team, 1872 (SLSA B69996/15)

This and other examples of visual representation taken during the expedition confirm Todd's ongoing ability to manage his new-found image and public performances. One historian of the Overland Telegraph Line, Peter Taylor, has established that Sweet took several photos of the same group at this time, but that a second group shot, which pictured Todd in glasses, was discarded, possibly at his own insistence in order to maintain the outback image of his party (Taylor 1980, p. 133). For he was becoming increasingly short-sighted, after spending long evening hours under hurricane lamps in his tent, writing letters and reports to the South Australian government as well as to Alice and his young family. Further press exposure, including a visual portrait in the *Sydney Mail* (1877), would follow at a later date. While the *Mail*'s reproduction lacked the sharpness of the earlier *Sketcher*'s woodcut, it retained the same formality, with a weary looking Todd wearing the Companion of the Order of St Michael and St George (CMG) medal, which he had duly received from the British government for his exertions.



SUPPLEMENT TO THE SYDNEY MAIL, SATURDAY, JULY 14, 1877.

CHARLES TODD, ESQ., C.M.G.,
POSTMASTER-GENERAL OF SOUTH AUSTRALIA.

See page 7.

MR. CHARLES TODD.

ON the first page of our supplement we give a portrait of a distinguished colonist, Mr. Charles Todd, Postmaster-General and Superintendent of Telegraphs, South Australia. He has earned distinction otherwise than by the ability displayed in the discharge of his official duties. On leaving school he entered the Royal Observatory, Greenwich, as an astronomical calculator (or computer), in January, [illegible]. He was subsequently appointed Junior Assistant Astronomer at Cambridge University Observatory. In [illegible] he was appointed, on the recommendation of the Astronomer Royal, Assistant Astronomer at the Royal Observatory, Greenwich, and had charge of the galvanic department. In 1855, on the recommendation of the Astronomer Royal, he was appointed by the Secretary of State as Government Astronomer and Superintendent of Telegraphs in South Australia, and arrived at Adelaide in November, the same year, bringing materials for the proposed telegraph between Adelaide, Port Adelaide, and Gawler Town, which lines were opened shortly after the first line in January, [illegible]. Soon after his arrival he submitted to the Government of South Australia a scheme of intercolonial telegraphs connecting immediately Adelaide and Melbourne; and in July, [illegible], he was despatched by Government to Melbourne to negotiate with that Government, and returned overland to Adelaide to decide on the best route for the line. His report on the scheme, giving estimated cost of work, &c., was laid before Parliament, and the amount was voted the following year, and the work in both colonies commenced, the line being opened right through in July, [illegible]. About that time he first submitted, in a letter to Sir Richard Macdonnell, a plan of a telegraph across the continent from Adelaide to the neighbourhood of Cambridge Gulf, following very much the route since adopted, except that he then proposed going to the Victoria River instead of Port Darwin. This proposal was embodied in a despatch from the Governor to the Secretary of State in [illegible]. It was always a favourite idea with him, especially after the explorations of Mr. Stuart proved it to be practicable, and he brought the matter not only before the Government, but also in a long paper which he read before the Philosophical Society in [illegible], when Sir Dominic Daly occupied the chair. A vote of thanks was proposed by the then Chief Secretary, Mr. G. M. Waterhouse. In January, [illegible], in addition to his duties as Superintendent of Telegraphs, he was appointed Postmaster-General; and in May that year, on the arrival of Commander Noel Osborne, R.N., he strongly urged that South Australia should undertake the erection of an overland telegraph to Port Darwin, to which point the Telegraph Company proposed to bring their cable. The Hon. H. B. T. Strangways, who was at the head of the Government, was also equally in favour of the scheme, which had besides the support of His Excellency Sir James Fergusson. The work, as is well known, was successfully accomplished, notwithstanding enormous difficulties which necessitated his going personally to the Northern Territory. An interesting account of this visit is given in the last published official handbook of the colony, by W. Harcus. At the present time Mr. Todd is actively engaged in carrying out the South Australian portion of a line of telegraph to Western Australia. The South Australian section starts from Port Augusta, at the head of Spencer's Gulf, via Port Lincoln, Streaky, and Fowler's Bay, and terminates at Eucla, a distance of nearly [illegible] miles from Port Augusta, and [illegible] miles of wire from Adelaide. It is hardly necessary to inform those who have read Eyre's and other explorers' accounts that it traverses the most [illegible] difficult country, and having been carried out in the face of a protracted drought, these difficulties have been enormously increased by the absence of food as well as water. The greatest distance without water occurs between Fowler's Bay and Eucla, where they have two stages, one over [illegible] miles and another over [illegible] miles, without either water or feed. Much of this country is covered with dense scrub, through which the line passes along a clearing of thirty to forty feet wide; but there being no serviceable timber, he had to use iron poles throughout. This work is now, so far as South Australia is concerned, nearly completed, and that colony will then have [illegible] miles of telegraph and [illegible] stations. In addition to his duties as Postmaster-General and Superintendent of Telegraphs, Mr. Todd is Government Astronomer, and in that capacity took an active part in observing the transit of Venus in December, [illegible], and has recently contributed some valuable observations of Jupiter. He is also carrying out an extensive system of meteorological observations. Our engraving is from a photograph by Mr. J. H. Newman, Oxford-street, Sydney.

Figure 4. 'Mr. Charles Todd', Supplement to *The Sydney Mail*, Saturday, 14 July 1877

A high point in the extensive press coverage, surrounding the Overland Telegraph Line and its aftermath, was the address which Todd delivered in July 1873, reviewing the planning and building of the Line. The *Sydney Mail* (1872) provided both positive and extensive coverage of Todd's endeavours to its band of readers, while the *Empire*, another Sydney

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organ, echoed the *Mail*'s sentiments after Todd delivered his well-attended lecture to the Adelaide Philosophical Society, declaring that 'Mr Todd has been the leader in this great work' and recommending his lecture 'as a chapter of public interest in the history of Australia' and 'an example of perseverance that ought to encourage everyone who reads it to renewed exertion' (1873). The *Mail* brought to light Todd's long association with the idea of an overland line to northern Australia, 'except that he then proposed going to the Victoria River instead to Port Darwin'. The notion that Todd had pointed the way, rather than simply following Stuart, continued to be a controversial one, but was part of the popular acclaim which attached to him from that time.

In spite of Sweet's iconic portrait and Todd's address, colonial newspapers were beginning to publicise different images of the now famous civil servant in which his authority as a scientist was also recognised. A wood engraving, commissioned by the *Australasian Sketcher* (1873) for its follow-up piece on Todd drew not on the iconic Roper photograph, but on a more formal one, as befitting a senior civil servant of the colonies. Moreover, the context of the article was quite different from Sweet's Roper River photograph. Despite previous attempts to identify Todd with outback exploring and adventure, the *Sketcher*'s carefully lithographic reproduction, which the Adelaide *Register* (1873) commended as 'excellent,' depicted its subject as bearded with spectacles. Moreover, the *Sketcher* piece chose to include the fact that Todd was also 'well versed in electrical science', with impeccable British credentials ranging from Royal Astronomical Society membership, to meteorology and electrical engineering. It represented a different Todd, one which would remain largely unknown to the public throughout his lifetime, though of interest to future biographers.

The Twentieth Century

In contrast with the nineteenth-century literature, which included biographical sketches in the Victorian heroic tradition, twentieth-century output on Todd was more selective. After Federation in 1901, Todd's profile inexplicably diminished in the press, despite the remarkable output of obituaries and tributes which occurred in 1910 at the time of his death. What survived nevertheless was a tradition of writing about the Overland Telegraph Line and its creator on the part of professional bodies, often at State as much as Federal level. This historical commentary on the Overland Telegraph Line, in contrast with the celebratory tone of the colonial press, gave way to a more sober strain during the early twentieth century. A sizeable body of writing and research on the part of engineering and postal societies, it was based upon a continuing consensus that, of all the notable developments in early Australian communication, 'none (is) more interesting and indicative of the tenacity and pertinacity of the pioneers than that of the establishment of the overland telegraph line' (Cameron 1945,

p. 189). By 1972, a century after its construction, and with the national press joining in the commemoration, the historic verdict remained unchanged. For B. E. Woodrow of South Australia (1972, p. 167), the Overland Telegraph Line was still 'a remarkable feat which ranks in the forefront of Australian pioneering achievements'.

At the national level, the Telecommunications Society of Australia played a significant role in bringing regional and state-based writing on the Overland Telegraph to the attention of a wider readership after its inception in 1935. Its regular publication, the *Telecommunication Journal of Australia*, undertook to reprint and serialise local contributions by writers on early telecommunications. Thus, A. R. Cameron's lecture, 'The Story of the Overland Telegraph Line', after first appearing in *Postal Notes* in 1932, was reprinted by the *Telecommunication Journal* in 1945. Its serialisation of Cameron's long monograph on the subject corresponded with renewed interest in Northern Australia and the Overland Telegraph in the wake of World War Two. For as Moyal (1984, pp. 153-159) and Bowden (2016) have noted, the Overland Telegraph Line, which continued as the main source of wartime communication between Darwin and the rest of the continent, was rapidly upgraded at that time for the purposes of telephony.

Articles such as Cameron's in turn influenced Todd's biographers later in the century, both George W. Symes who first took up the task in South Australia, and Kevin Livingston who, after publishing *The Wired Nation Continent* (1996), began gathering material for a biography. Livingston, whose papers passed to the author after death, made annotations on his copy of Cameron's 1945 article as he prepared to write a second volume, this time about Todd himself. In this respect, the twentieth-century output of the *Telecommunication Journal of Australia* provides a useful guide over time to the evolving literature on the Overland Telegraph and Todd's place within it. Although he was not as yet identified in mid-twentieth century as the subject of a life biography, Australian writers on telecommunications, including the prolific Frank Clune (1955), bequeathed Todd admirers a vast archive of documentation upon which to draw, much of it scattered across South Australia's voluminous parliamentary papers and archives, along with company records and manuscript material held in Telstra's Sydney archives.

Any sustained biographical endeavour would need to draw upon and synthesise these diverse sources. In the meantime, Todd's long and detailed official reports, written during and after the Overland Telegraph Line's construction, were given the highest priority by writers. These were generally cited verbatim and often at length (Cameron 1945, pp. 195–198) as the essential primary source on the subject, since they were informative, not only of Todd's own intentions but of rival colonial schemes in response to proposals by competing British companies to construct underwater cables from Asia to different points of the Australian coastline.

Apart from its emphasis on primary material in the form of technical reports, the strength of such professional writing on the Overland Telegraph Line lay in its familiarity with outback conditions and exploration on the part of pioneers like John McDouall Stuart. Neither superficial nor journalistic, it was often extensive. Cameron's account, which exceeded fifty pages, was published by the *Telecommunication Journal* over several issues, rather than as a single monograph. In keeping with the longstanding consensus of the early twentieth century concerning outback pioneering, such accounts set out to revive interest in an 'engineering feat … unparalleled in the history of Australia', albeit by focusing on particular aspects of planning and technology, rather than on the undertaking as a whole.

By 1972, the Overland Telegraph centennial commemorations promised a resurgence in writing and research on Todd and his telegraphic exploits, this time with a national focus. An example to appear in the *Telecommunication Journal* of that year was the series devoted to Telecom's operations in the Northern Territory, to which staff from different States contributed. Its discussion of the Overland Telegraph Line was prefaced with a detailed explanation of the development of telegraphy and of the systems in use at that period. After noting Todd's success on the Roper River in restoring the northern leg of the expedition (Woodrow 1972, p. 173), the *Telecommunication Journal* series continued its account of the line into the twentieth century with a discussion of post-World War 2 developments in voice communication and machine telegraphy (Todd 1972), including the North-South reconstruction project of 1965. In the process, it drew parallels between present and past. But if the flooded conditions encountered in the 1960s recalled those endured by Todd and his parties and again made 'the use of mechanical aids impossible' (Todd 1972, p. 178), modern Telecom operations enjoyed the advantage of motor transport such that 'the facilities afforded by the bitumen and air transport enabled the work to proceed with some degree of efficiency'.

In the same year as the Northern Territory series appeared, a prominent South Australian and Royal Geographical Society President, G. W. Symes (Symes, 1977-80) was also at work on a history of the Overland Telegraph Line, one which would surpass most previous accounts in its length and detail. Essentially a multivolume collection of primary documents, it continued the tradition of documentary analysis begun earlier in the twentieth century, while including extracts from the journals of leading actors in the great construction project. By incorporating journal material, Symes sought to inject personal experience into his account, not least Todd's movements in the field. Symes' lengthy account, which was never published, also sought to situate Todd within his time by including essential developments in telegraphy, initially in Britain and subsequently in the Australian colonies. From a biographical as well as professional perspective, it was no longer simply enough to focus on the great Overland Line. Firstly, he would have to discuss Todd's earlier experiences building telegraphs across Australia and the ways he adapted his imported equipment to colonial conditions, not only his insulators but the language of Morse code, adopted on the advice of his Victorian colleague, Samuel McGowan.

Figure 5. Charles Todd standing in studio, c. 1871 (SLSA B6793)

At a time of nationalism and commemoration of great Australians, Symes recognised Todd's untapped potential as a national hero, as proclaimed by colonial newspapers. With Symes' untimely death in 1980, however, it fell to others, most notably Kevin Livingston and Ann Moyal to explore the fertile historical associations between Todd's long and distinguished career and broader developments in telecommunications. If Symes' use of journals and diaries strengthened the case for a biography, Livingston's *Wired Nation Continent* (1996) added to the already extensive archive on Todd and colonial telecommunications by undertaking an ambitious analysis of the many intercolonial Post and Telegraph conferences in which Todd figured prominently. At the same time, Livingston emphasised the role played by the press in these deliberations, as state-based newspapers upheld regional interests on a range of communication issues.

As biographers, Symes and Livingston, employing different historical sources, chose to approached Todd at different periods of his career: Symes worked backwards in time to his earlier years, while Livingston worked forwards in time from the Overland Telegraph years (1870-72) to the end of the nineteenth century. In combination, their research helped provide the broad framework for an in-depth biography. In the process, both scholars contributed new biographical entries on Todd: Symes (1976) to the *Australian Dictionary of Biography* and Livingston to the *Oxford Dictionary of National Biography* (2004-2010). In the course of his searches into Todd's early years, surely the starting point for any major work, Symes spent many years gathering material from sources in the United Kingdom with variable results, while Todd's later years remained, if anything, even more obscure. Uncertainty persisted over the family record, while Todd's own limited writing on the subject proved a further barrier to detailed biographical inquiry. Nevertheless, Symes' research into Todd's background informed Peter Taylor's *End of Silence* (1980) which blended a detailed account of the Overland Telegraph construction with biographical elements at the beginning and end of his book.

From a biographical point of view, sporadic references to Todd's correspondence with Alice during the critical construction phase in the Northern Territory added further to the expanding archive on Todd. In its brochure devoted to Todd and the Overland Telegraph Line, Telecom (1979) alluded to 'Todd's Alice' of Alice Springs fame. Though largely absent from previous accounts, their lengthy correspondence during 1871–72 provided fresh evidence that a synthesis of Todd's public and private activity was not only possible, but even necessary for biographical purposes. Significantly, the 2017 biography draws in some detail on the writings of Todd women, particularly those of Todd's youngest daughter, Lorna. Along with Alice's regular letters, Lorna's serialised newspaper articles on both her parents many years later opened a biographical window onto the Todds' Australian years.

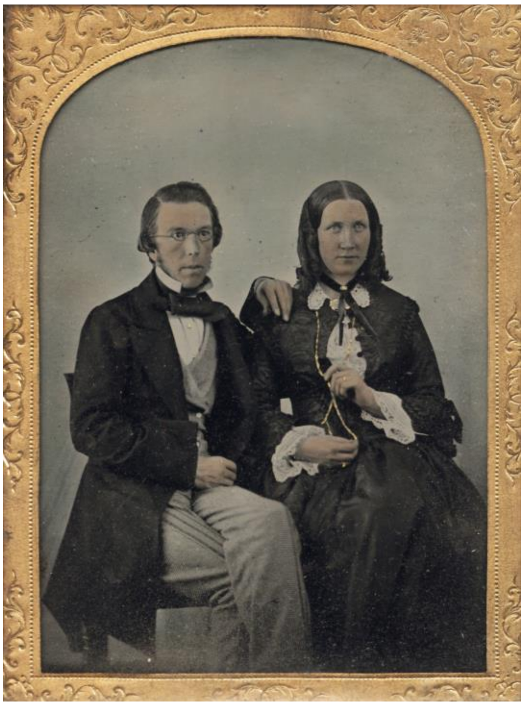

Figure 6. Charles and Alice Todd, c. 1855, Glass Plate (SLSA B69996/9)

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The Twenty-First Century

By the twenty-first century, when Donald Lamberton (2001) delivered an important address to the Telecommunications Society for its annual Todd Oration, the mood had changed from centennial celebration to one of frustration at the absence of a detailed Todd biography. A distinguished if unconventional economist and a 'non-historian' in his own words, Lamberton (2001, p. 66) appeared an unlikely successor to Kevin Livingston, whose 'excellent' *Wired Nation Continent* he commended to the audience for its insights into the nineteenth-century communication revolution and federating Australia. In canvassing what had by now become the Todd 'centennial challenge', Lamberton was interested as much in the Overland Telegraph episode as 'an important event in Australian history', as one 'that helps us understand better what is going on now' (2001, p. 66). Consequently, he drew upon his contemporary expertise in the fields of innovation, telecommunications and the knowledge economy when subjecting Todd's ambitious Overland Telegraph project to the rigours of contemporary technology assessment. In spite of the serious difficulties confronting Todd — 'the timeless and waterless desert', not to mention the distance, cost and organisational challenges — Lamberton was still of the view that the OTL project would 'pass the test of the assessment standards … by modern committee' (2001, p. 66), on the basis of its sound management plan and the access it promised to world markets.

Although some of his fellow economists (Mathias 1983) voiced suspicion of an historical interpretation of technological innovation based solely upon the work of prominent individuals, Lamberton preferred to see Todd's great venture as an essential part of Australia's 'first great globalisation'(2001, p. 70). Consequently, he remained enthusiastic about the value of a Todd biography, calling for a 'big thick life … rich in detail'. Acknowledging the recent appearance of a 'lively paperback', *The Singing Line* by Todd's great-great-granddaughter Alice Thomson (1999), Lamberton rightly insisted that the difficult work of drawing together archives and collating Todd's widely scattered papers had yet to be done, in order for the full story of his career to be told. Admitting that his own project on Todd was still in 'its early days', Lamberton identified Ann Moyal as the main source of his inspiration, for her monumental *Clear Across Australia* had given him a better appreciation of 'an historical perspective and the way it links with my inclination to see economic events in narrative terms rather than as a succession of optimising solutions' (2001, p. 66).

Moyal's willingness to take on the challenging task of Australia's telecommunications historian, in the first instance, owed something to Lamberton's influence within Telecom. Her impressive national history, published in 1984, not only stimulated biographical interest in Todd but drew together many strands of twentieth-century professional writing on the telegraph. In the Preface to *Clear Across Australia*, she confirmed her broad intention of 'depicting the leaders and planners … the part played by individuals and teams, inventors and innovators and the influence of engineers', while exploring changing workplace conditions and the 'wider economic, financial and social interactions of telecommunications within the developing community' (1984, p. xii). Moyal's task, admirably fulfilled, incorporated biographical elements and aligned with Lamberton's judgement of Todd as an innovator, engineer, a 'great manager' and good people person, capable of inspiring his workforce and mounting an eloquent public case for the benefits of the new technology (2001, p. 68)

In hindsight, the dramatic changes which occurred in telecommunications by the 1980s served to enhance Todd's legendary reputation in the opinion of historical scholars. Thus Moyal (1984, p. 386) concluded her book by lamenting Telecom's failure at times to communicate its technological successes to the public, in favour of 'bland bureaucratic pronouncements on work-related issues'. By contrast, she remained generous in applauding Todd's capacity to promote and implement his bold management plan for the Overland Telegraph Line — a project which she considered 'the greatest engineering feat in 19th century Australia' (1984, p. 42).

Figure 7. Charles Todd with the Order of St Michael and St George medal, 1880 (SLSA B69996/19)

Genesis and Aims of the Current Biography

My recent Todd biography, *Behind the Legend*, owes a considerable debt to both Moyal and Lamberton, not least for their assistance in making available files collected by Kevin Livingston before his untimely death in 1998. Livingston's interest in Todd was not that of a local professional or historian. Rather, as Lamberton rightly noted, he anticipated the global thinking of the new telecommunications history, in seeking to place Todd and his telegraph in a broader geopolitical perspective. One biographical conundrum associated with Livingston's work was the place and contribution of colonial newspapers to the painstaking task of documenting his life and career. Colonial newspapers took to the telegraph as a source of overseas and intercolonial news, yet was this their main or indeed only focus in Todd's case? More fortunate than Livingston and historians before him, the author was able to access an extensive range of sources and newspaper commentary, using the recently digitised Trove Australian newspaper database. What became clear, after extensive consultation and name searches, was that Todd attracted nation-wide coverage not only for his telegraphy but also for a range of other activities, among them meteorology and astronomy.

As the centenary of Todd's death approached in 2010, the production of a comprehensive biography appeared more daunting than ever. By the twenty-first century, Todd's detailed reports were now being mined by a wide range of disciplines, most notably in South Australia where a 2012 Symposium (Australian Meteorological Association, 2012), convened for the 140th centenary of the Overland Telegraph, documented his diverse professional contributions across fields as diverse as astronomy, telegraphy, electrical engineering, postal services, meteorology and surveying. At the same 2012 event, the author of this article (Cryle 2012) argued that a biography could provide fresh perspectives on Todd's wide-ranging activities, not least upon the well-documented and powerful story of the Overland Telegraph, in order to better understand Todd's personality under pressure. The neglected correspondence between Charles and Alice during that critical period provides important insights into Todd the manager, as well as Todd the family man. For the biographer, these two aspects are inseparable.

Increasingly, as the 2012 Symposium and recent literature demonstrate, Todd is being studied as a scientist rather than exclusively as a pioneering telegraphist. This shift in emphasis, whether it be on his weather work, astronomy or administration, preceded the 2012 Symposium and continues to gather pace in the twenty-first century (Benoy, 2011). This is in itself a welcome trend, quite distinct from the professional writing of the twentieth century and is testimony to Todd's remarkable capacity to manage his time as well as that of others. Yet, while it may no longer be correct to simply label him as 'Telegraph' Todd, it would surely be too simplistic to describe the Overland Telegraph as merely one interlude in his long and productive life. *Behind the Legend* sets out to balance the different aspects of his long career, including the tensions which this produced, without losing sight of his well-earned reputation for telegraphy. It confirms that Todd dreamt of his 'great work' from his London days, well before he undertook it in the 1870s. Moreover, he continued to manage and maintain the Overland Telegraph Line for another three decades after its construction, surely a unique feat in the history of early Australian telecommunications for which he should also be remembered.

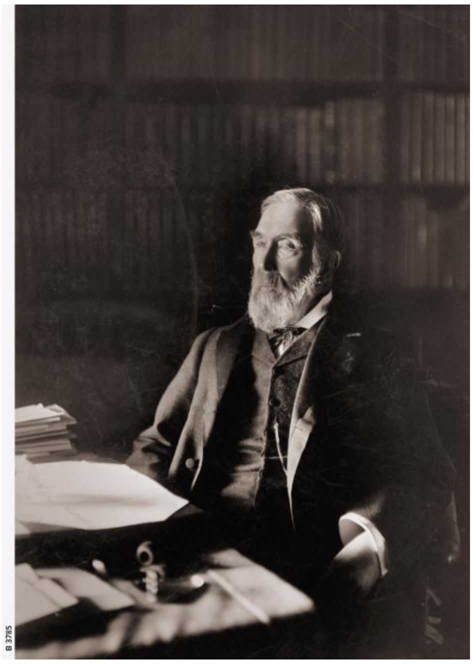

Figure 8. Charles Todd in his library, c. 1900 (SLSA B3785)

Among the pressing biographical challenges flowing from the 2012 Symposium was how to structure Todd's diverse achievements as a life history, without losing the seminal telecommunications thread which brought him to Australia and projected him into public life. Livingston's investigation of Todd's later Postal and Telegraph conferencing confirms the persistence of telegraphy as a narrative thread, starting with his activities in England at Greenwich and continuing into his later years in Adelaide. In keeping with Lamberton's concerns, the biography includes six detailed chapters relating to the telegraph, both before and after the great overland project, interspersed with accounts of his scientific and managerial activities, including his observations of the transit of Venus, reorganisation of the South Australian post office and establishment of a meteorological network across the same colony.

From a professional perspective, Todd's modernity resides in his capacity to move between old and new technologies. He relied on the technology of the telegraph to pursue his wide-ranging scientific activities. Yet, as an experienced civil servant, he was also highly print literate. Not only did he continue to produce voluminous reports, but his extensive correspondence, largely neglected like his letters to Alice, invited much closer scrutiny. In its three-part structure, the biography adopts a broadly chronological narrative: starting with Todd's formative early years in Britain and South Australia; continuing into Todd's most energetic phase during the 1870s and 1880s, of which the Overland Telegraph Line episode was an essential part; before documenting his no less interesting or challenging later years,

The NBN of Its Day

In conclusion, one should ask, following Lamberton, what light Todd's project, described as 'the NBN of its day' (Berroeta 2016) casts on the dynamic telecommunications field today. Our technological awareness has greatly advanced over time; yet many of the challenges facing Todd in the nineteenth century still persist. These include the risk of spiralling costs and substantial delays, as well as the effectiveness of the technology employed, not to mention the bipartisanship of the political process, some of which Lamberton identified in his 2000 Oration. The Todd biography will not resolve all these issues, indeed it may well rekindle others. Some scholars (Putnis 2008) continue to dispute how well the Australian colonists fared in negotiations with that great global monopolist, the Eastern Extension Telegraph Company, which first brought the underwater cable to our shores. Was Todd acting on behalf of South Australia only, as Livingston implies, or in the national interest? How exceptional was his persistence, technical capacity and networking ability? The 2017 biography confirms that Todd was unusual, after waiting almost a decade for colonial co-operation, in going it alone into the Red Centre. On this basis, one is entitled to ask whether such great projects as the Overland Telegraph Line should be undertaken at State rather than Federal level, as the South Australian government decided to do? Should new telecommunications projects be confined to established cities — the 'golden triangle' concept? While undoubtedly providing inspiration and an important sense of the past, *Behind the Legend* does not attempt to answer such questions. But it does allow a detailed examination of the emerging telecommunications field at one important moment. Todd continued to believe that the long-term benefits of his scheme outweighed the immediate challenges of the difficult implementation process. He flew in the face of criticisms levelled at his 'mad scheme', and managed the difficult adjustment period after its construction. Such is his national legacy, for which we extol his perseverance.

Despite differences in biographical perspective — differences which have emerged in the recent literature on Todd — historians of both technology and science concur that Todd grew up and worked in an unusually dynamic period and place, where the nineteenth-century information revolution was transforming society and expanding its networks. As with other great infrastructure projects, writers have been inclined to view such achievements as the work of many actors, a consensus which underpinned the professional literature on Todd for much of the twentieth century. Sceptics in Australia would continue to cavil at the benefits and cost of large-scale projects, dismissing them as 'white elephants' and querying the motives for their promotion. In an age when public service still counted for much and levels of political and public scrutiny were high, Todd's financial motives were above reproach. As a model civil servant, he was not content simply to follow, and was prepared to proceed alone, a decision for which critics labelled him as rash and egotistical. In relating such challenges, the biography cannot simply assume success, reminding readers all the while of the ongoing risks of thinking and acting on such a scale.

Conclusion

In conclusion, this article has sought to examine both the gaps and biographical possibilities in the lengthy Todd literature. As a comprehensive and challenging genre, biography offers a means of further understanding Todd's unusually long and distinguished career. Yet that long trajectory, as this article also shows, has not been without its difficulties. Although Todd was a product of working-class Greenwich, his capacity to seize the opportunities around him was unusual. In particular, the biography set out to capture his exceptional commitment and energy, qualities which have rightly earned him a special place in Australian telecommunications history. There is little doubt that Todd considered his cherished scheme to be a nation-building one. The protracted federation process and its political fallout may have overtaken his departments and dispersed his achievements. But the long-awaited biography confirms his status as a great Australian who led by example and put in place the necessary infrastructure for the emergence of a modern nation.

References

Australasian Sketcher. 1873. 'Sir Charles Todd,' 12 July 1873, p. 72.

Australian Meteorological Association. 2012. Sir Charles Todd Symposium, Adelaide.

Benoy, M. 2011. 'The birth of the familiar everyday map', *The Globe Journal of the Australian and New Zealand Map Inc*, vol. 67, pp. 9-22.

Berroeta, I. 2016. Sir Charles Oration, Sydney, October.

Bowden, B. 2016. 'The Bombing of Darwin'. *Australian Journal of Telecommunications and the Digital Economy*, vol. 4, no. 1, Article 44. http://doi.org/10.18080/ajtde.v4n1.44 (link is external).

Brisbane *Telegraph*. 1872, 'The Adelaide Port Darwin telegraph', 8 November. Cited in Todd to the Colonial Secretary, 2 December 1872 (South Australian Parliamentary Papers, 1873, no 26)

Cameron, A. R. 1945. 'The Story of the Overland Telegraph Line', *Telecommunication Journal of Australia*, vol. 5, no. 4, June, pp. 189-198 and October, pp. 283-289.

Clune, F. 1955. *The Overland Telegraph. An epic feat of endurance and courage*, Sydney: Angus and Robertson.

Cryle, D. 2012. 'Charles Todd and the Overland Telegraph Line: a biographer's perspective', Adelaide, 17 August.

Cryle, D. 2017. *Behind the Legend: The Many Worlds of Charles Todd*, Melbourne: Australian Scholarly Publishing.

Dowling, P. 1999 'Truth versus Art in nineteenth-century graphic journalism: the colonial Australian case', *Media History* vol. 5, no. 2, December, pp. 109-126.

Empire, 11 August 1873, editorial, p. 2.

Illustrated London News, 1873. 'The Australian Telegraph', 22 February, pp. 1-2.

Lamberton, D. 2001, 'The Subversive and the manager: organizing knowledge in a hard place - The Charles Todd Oration', *Telecommunication Journal of Australia*, vol. 5, no. 1, Autumn, pp. 65-72.

Livingston, K.T. 1996 *The Wired Nation Continent*, Melbourne: Cambridge University Press.

Livingston, K. 1997. 'Charles Todd: powerful communication technocrat in colonial and federating Australia', *Australian Journal of Communication*, vol. 24, no. 3, pp. 1-10.

Livingston, K.T. 2004-10. Sir Charles Todd entry, *Oxford Dictionary of National Biography*, Oxford University Press.

Mathias, P. 1983. 'The machine: icon of economic growth', in S. MacDonald, D. Lamberton and T D Mandeville (eds), *The Trouble with Technology. Explorations in the Process of Technological Change*, London: Frances Pinter, ch. 3, pp. 11-25.

Moyal, A. 1984. *Clear Across Australia: A history of telecommunications*, Melbourne: Nelson.

Putnis, P. 2008. 'The early years of international telegraphy in Australia: a critical assessment', *Media International Australia*, no. 129, pp. 140-148.

Sebe, B. 2009. 'Colonial celebrities in popular culture: heroes of the British and French empires, 1850 – 1914', in Robert Clarke (ed.), *Celebrity Colonialism: fame, power and representation in colonial and postcolonial cultures*, Newcastle upon Tyne: Cambridge Scholars Publishing, pp. 37-54.

South Australian Register, 8 July 1873, p. 6

Sydney Mail, 16 November 1872, editorial, p. 2.

Sydney Mail, 14 July 1877, Supplement, p. 86.

Sydney Morning Herald. 1872. 'Telegraphic Communication between England and Australia,'16 November 1872, p. 6.

Symes, G. W. 1976. Sir Charles Todd entry, *Australian Dictionary of Biography,* Melbourne University Press, vol. 6.

Symes, G. W. 1977-80. Life of Sir Charles Todd, MSS, 2 vols.

Taylor, P. 1980. *An End to Silence. The building of the Overland Telegraph Line*, Sydney: Methuen.

Telecom. 1979. *The Overland Telegraph Line*, Sydney.

Thomson, A. 1999. *The Singing Line*, London: Random House.

Todd, A. 1872. Letter to Charles Todd, 1 August 1872. Todd Family Correspondence, State Library of South Australia (PRG 630/2/8).

Todd, C. 1872. Letter to Alice Todd, 2 March 1872 (PRG 630/2/26).

Todd, R M 1972 'A century of telecommunications in the Northern Territory. Part 2: The Overland Telegraph', *Telecommunication Journal of Australia*, October, pp. 174-182.

Woodrow, B. E. 1972. 'A century of telecommunications in the Northern Territory. Part 1: The Subsequent Development of the Route', *Telecommunication Journal of Australia*, October, pp. 167-173.

Behind the Legend

A new and comprehensive biography of Charles Todd

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Abstract: In 2017 a new biography, ***Behind the Legend - The Many Worlds of Charles Todd,*** by Denis Cryle, was published. The biography seeks to provide a more complete understanding of Charles Todd beyond the single achievement for which he became most famous – the building of the Overland Telegraph Line linking Darwin and Adelaide in 1872. The biography lives up to its promise and sets out in considerable detail the contribution that Todd made in many fields during his long lifetime and period of public service. Those fields include astronomy, meteorology, telegraphy, telecommunications more generally, public administration, and contribution to the processes of federal coordination and cooperation. Todd's fame and legacy have been heavily bound up with the construction of the Overland Telegraph Line. As Cryle notes, he was dubbed 'Telegraph Todd' by the media of the day.

It is the stated purpose of Cryle's biography to do justice to Todd across the *full* range of his achievements. I think that Cryle succeeds admirably. He has written an engaging book that is thoroughly researched and referenced. It will appeal both to historians and to the general reader without expertise in any of the scientific or technical fields inhabited by Todd.

Keywords: Book review, Charles Todd, telegraphy, meteorology, astronomy, Adelaide, public administration, standard time.

Introduction

A new biography of Charles Todd by Australian academic Denis Cryle should be of interest not only to the reader interested in special areas of expertise associated with Todd's career and contribution, but to the general reader as well.

The biography is ***Behind the Legend – The many worlds of Charles Todd***, and was published in 2017 by Australian Scholarly Publishing.

Cryle has a number of aims in writing this well researched book, and the most important, as the title suggests, is to ensure that a complete biography, which describes the wide diversity of Todd's interests and contribution, is written. Previous biographies have tended to concentrate on the Overland Telegraph Line linking Darwin and Adelaide. Many studies of Todd have mentioned his contribution to meteorology, astronomy and public administration, but as very much secondary to telecommunications – and to telegraphy in particular. This is hardly surprising, since they are reflecting the media focus of Todd's time and the main focus since. However, as Cryle notes, more recently historians have rectified the situation to some extent.

The introduction to the biography carefully reviews the changing approach to Todd's profile over the years. An overview of that changing profile appears in Cryle's article in this issue of the Journal. He notes Kevin Livingston's comment that Todd was 'well on the way to becoming a legend' by the age of 46 – that is, by the time of the successful completion of the Line in 1872. He also indicates how Todd's reputation and influence grew within his lifetime – within South Australia, at the inter-colonial level in Australia and also internationally. It becomes clear that Todd was a consummate networker and developed a wide range of professional and personal associations that were typically deep and lasting over the course of his long life. In the end he outlived many of his associates. He worked as an eminent civil servant until his 80th year and died in 1910, aged 83. Cryle also demonstrates in his introduction – and in the article in this issue of the *Journal* – how Todd's profile has evolved since his death, and how more recent historians have 'done much to revive Todd's reputation in meteorology' for example (Cryle 2017, p. 10).

Structure

The biography is very well structured to develop certain themes that occupied Todd's life at various stages, but always with the reminder that other matters are progressing and developing in parallel. In this way, Cryle successfully maintains a connected narrative of Todd's life but also maximises the focus and understanding of the key issues at any given stage in that life. This approach of overlaying themes on the timeline is most effective. After reading the book, I think that no other structure or organisation of the voluminous material could have worked as well.

The biography is organised into three Parts:

- Part I (1841-55) deals with Todd's early years in the British civil service and his employment at the Royal Observatory in Greenwich; and his introduction to telegraphy as a means of developing accurate time measurements.

- Part II (1856-86), in which he is located in Adelaide and oversees the building of the Overland Telegraph Line. Also in this period there are many other matters that occupy Todd and to which he makes a lasting contribution, including the reorganisation of the Posts and Telegraph department in South Australia and the establishment of the Adelaide Observatory.
- Part III (1887-1910), in which Todd continues his major contributions to postal administration, telecommunications, meteorology and astronomy, but also transitions from colonial to federal civil service.

In all of these periods Todd had to deal with a vast array of people and issues, and in this he demonstrates considerable skill and effectiveness – including in dealing with difficult or demanding masters, ranging from academic bosses such as Sir George Airy, the Astronomer Royal, to the many colonial and federal counterparts (some cooperative and some competitive) and to the politicians of the times, especially in South Australia but also in other colonies and later at the federal level. In the overwhelming majority of cases Todd developed respectful professional and, often, personal relations that lasted for the long term. There were exceptions.

Cryle notes that Todd's early years in the UK and last years have been 'neglected' by historians, on the whole, and he makes good the oversight.

Cryle also makes the interesting claim, one that is well supported by the material in the biography, about the importance of astronomy in understanding Todd's life: 'Less visible as the nocturnal component of his career, astronomy was to remain an important unifying principle across the different phases of his life' (Cryle 2017, p. 11).

Making good from humble origins

One theme of universal appeal to the general reader is that Todd was of humble origins and that his achievements were borne on the back of persistent hard work. No expectation based on privilege was involved in the least. His father's business as a grocer was precarious. Todd's formal schooling ceased at age 15 and he went to work as a 'computer' at the Royal Observatory, Greenwich, then ruled by George Airy, the Astronomer Royal, undertaking calculations of the location of planets when observed at various times. Cryle describes the conditions and strictness of the working environment that Todd experienced as he laboured for 8 hours each winter day and for 12 hours in summer. Todd's vital opportunity came when he was appointed as a junior assistant in the observatory at Cambridge. It was while posted at Cambridge that Todd worked on improving the accuracy and distribution of time signals via telegraph between observatories and other observation points.

It was this experience that led Airy to require Todd back at Greenwich from 1854 where his duties involved detailed collaboration with the Electric Telegraph Company and railway companies in joint time distribution projects. The railways wanted to establish regular scheduled service based on accurate time distribution.

Cryle describes in some detail how the work progressed and the initiative demonstrated by Todd that raised him considerably in Airy's estimation and singled him out for the next assignment – a position in the colony of South Australia as superintendent of electric telegraphs 'with desirable experience in astronomical and meteorological observation' (Cryle 2017, p. 49).

Adelaide and the 'great work'

Part II deals with the middle years of Todd's career in Adelaide, from 1856 until 1886, and the planning and construction of the Overland Telegraph Line. Cryle's coverage of the issues that had to be overcome leading up to and during construction is comprehensive and, if this was the main purpose of general readers in consulting the book, they would not be disappointed. The coverage of other aspects of Todd's career is not at the expense of a sound rendition of this central achievement. At this time Todd's capacity for first-class project management and administration is on display, as well as his readiness to take charge in the field, when he stays encamped on the Roper River for months to address the problems of the northern section construction. Of particular interest is the politicking between the colonies, and especially the competition that emerged between South Australia and Queensland to build a telegraph line, as well as the cable politics played out at the Imperial level between companies in London. The description of the cable politics of the era, which went on for the remainder of Todd's career, is one highlight of the book.

Astronomy and Meteorology

As Postmaster General, Todd was the person primarily responsible for the establishment of an astronomical Observatory in Adelaide. It was located on West Terrace adjacent to the extensive parklands in that area at the time. (It has since been demolished and the site incorporated into the grounds of the Adelaide High School.) After slow progress, the building was completed in 1860. Equipment had to be shipped from the UK, although Todd showed innovation and flair in sourcing some materials locally.

In the colonial era it was normal for Observatories to undertake astronomical observations and to record meteorological events, with limited weather forecasts to assist farmers and others with special interest. It was only later, during the Commonwealth era, that a separate bureau of meteorology was established. As Cryle notes, Todd and others were well aware that the popular interest was in the weather and that astronomy was the poor relation when it came to public funding. Todd was not averse to cross-subsidising within his diverse portfolio as Postmaster General, and astronomical observations were funded off the back of meteorology and more general expenditures. He therefore opposed the centralisation of separate State weather operations into a single Commonwealth bureau, and would have had the proposed new central body undertake 'theoretical and scientific research' concerning 'the dynamics of the atmosphere' (Cryle 2017, p. 220). Todd's view prevailed at a conference of State delegates in May 1905, but that view was, in turn, effectively ignored by the Commonwealth (Cryle 2017, pp. 219ff.).

Cryle makes a very compelling case throughout the biography that astronomy was of fundamental importance to Todd and serves to provide a link from the earliest days of his career until the very end. He participated in global cooperative efforts, usually involving the Greenwich Observatory, to observe various transits of Venus, eclipses, comets and many other astronomically important events. Multiple observations were important not only to overcome local issues associated with cloud and weather, but also for basic calculations. Accurate timing was equally critical.

The weather wars

Another theme that is well documented in the book, and one that will resonate with the general reader, concerns the weather wars in the period from the 1880s to the early twentieth century. Today we are all used to the notion of competing forecasts offered by different media, but they tend to have a common base in Bureau of Meteorology data. Quite often the competition is in the presentation or the length of the forecasts, rather than the substance. By the early 1880s each of the colonies had established its own network of weather stations to report meteorological data. The data was distributed free of charge via the telegraph service. This established arrangement was disrupted by a Scotsman 'armed with a towering ego' (Cryle 2017, p. 204) named Clement Wragge, who set up his own independent network of self-registering stations which he planned to extend across Australia, starting in South Australia. Wragge was later appointed as the Queensland meteorologist, in 1887.

Cryle notes that 'Wragge's long and turbulent colonial career was marred by ongoing professional controversy, which thrived on confrontation and self-promotion' (Cryle 2017, p. 205). There is nothing new under the sun – contrarianism and notoriety have been the staple building blocks of many careers before and since Wragge.

Wragge broke with colonial consensus by issuing his own national forecasts in the late 1880s, and was very skilled in telegraphing them to media in all colonies. He wanted the same telegraph subsidy for his forecast distributions that each of the colonies afforded to each other. He also courted public opinion very well, because farmers wanted forecasts and the colonial meteorology units were loath to provide anything other than very short-term predictions. Todd, for example, was reluctant to stand by the accuracy of his forecasts 'beyond one or two more days' (Cryle 2017, p. 207).

I don't want to spoil the story that Cryle tells so well by repeating here how it played out. However, the controversy over competing national and local forecasts, and the Wragge incursion, continued well into the Commonwealth period with the establishment of a centralised bureau and the departure of one of the key protagonists.

Time Lord

The general reader might also be interested in the time wars that preceded federation, and of the key role played by Todd. Cryle entitles chapter 11: 'Time Lord: Todd's Elusive Pursuit of Standard Time in the 1890s'. Standardisation of time was important for telegraphy and other forms of communication, general commerce, shipping and railway operations. But there were a number of competing ideas about how it should be accomplished. At an inter-colonial conference in 1891, Todd recommended an hour zone system as well as a uniform standard time for all Australian colonies.

We have become used to adjusting for time changes since the progressive re-introduction of daylight saving time in Eastern and central Australia from 1968. However, none of these arrangements are anything like the change advocated by Todd, with a uniform time across Australia, based on the time at the 135th meridian (west of Adelaide). The three time zones that emerged, contrary to Todd's view, resulted after considerable public debate and media attention. The result was not inevitable, and was itself modified later for South Australia as a result of commercial pressure.

In this instance Todd was on the wrong side of history and his arguments seem particularly pedantic based on the differences between solar time and time on a clock. He seems to have underestimated the social importance and dimension of time. Adaptation to a uniform time across Australia would have affected the eastern colonies and Western Australia, but not South Australia. However, even though uniform time was rejected, standard time zoning was established.

Cable wars

It was one thing to build the Overland Telegraph Line, but quite another to keep it operating on a commercially viable basis. This ongoing struggle, and Todd's long-term success, is another theme that might resonate with the general reader. The issues of recovering capital and maintenance costs associated with major public infrastructure certainly have parallels with many other projects in Australian telecommunications history, including the NBN.

Todd was required to balance two potentially conflicting objectives – reducing retail telegraph and telegram prices on the one hand, and obtaining sufficient revenue to operate essential infrastructure on the other. This challenge applied to postal services in South Australia as well. The problem as we all know is that any price system that is carefully balanced for the longer term is vulnerable to technological and commercial disruption. So it was with international cable projects.

The Overland Telegraph Line was built as an extension to the colonies of the cable system that was operated as a monopoly by the British Australian Telegraph Company under the long-term direction of John Pender. Later cable projects, such as the Pacific cable project, were a major commercial threat over the following three decades, as was the potential for wireless communications as a result of Marconi's work.

The advancement of science

Cryle describes a range of activities that Todd initiated or supported that were ultimately about the advancement of science, not only in South Australia. The book describes his work in supporting the Australasian Association for the Advancement of Science (AAAS) from its formation in 1888. The building of the Adelaide Observatory has already been mentioned. As well, he served for a long period on the councils of Adelaide University, often in company with his son-in-law, William Bragg.

Conclusion

Cryle has provided a rounded portrayal of Todd, and has filled out the many other aspects of Todd's long and productive life. In the process, he has also provided a very comprehensive description of Todd's personal life and of the various members of the Todd family, as well as of the circles in which they moved. One therefore develops a good sense of the context and the times in which Todd lived and how he contributed to and helped shape them.

I have not discussed in this short review many of the other themes that Cryle considers, but they should also be mentioned. For example, the transition from colonial administrations to the Commonwealth, especially in relation to meteorology and posts and telegraphs, was fraught with politics, false moves and general mayhem. The treatment of many colonial public servants in the new federal system was very poor, and the quality of administration plunged for at least a decade.

Denis Cryle has produced a very thorough and highly readable account of the life of Charles Todd and I commend it to general readers as well as to those with particular interest in specific aspects of Todd's life and contribution.

Reference

Cryle, D. 2017. *Behind the Legend – The Many Worlds of Charles Todd*. Melbourne: Australian Scholarly Publishing.

The Weatherman from Greenwich

A new book 'about' Charles Todd

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Abstract: A new book, *The Weatherman from Greenwich: Charles Todd – 1826 to 1910*, promises to be a biography of Charles Todd, telecommunications pioneer in Australia. The title is, however, misleading. Most of the book is devoted to social influences in England and South Australia that may have shaped Todd's early life. Todd's early technical experience in England and his first activities in Australia are briefly sketched. Readers seeking a fuller account of Todd's life and achievements should look elsewhere.

Keywords: Book review, Charles Todd.

Introduction

A new biography of Charles Todd, one of the founding fathers of telecommunications in Australia, should spark interest in the readers of this *Journal*. This book, *The Weatherman from Greenwich: Charles Todd – 1826 to 1910*, by Tony Rogers and Judy Ferrante (Rogers, 2017) carries the subsidiary title on its cover: "Meteorologist, Telegrapher, Electrician, Postmaster-General, Astronomer, South Australian". It thus promises to be a full picture of the man and his achievements. Alas, it falls far short of this promise. Those who seek a more complete biography of Todd should look elsewhere.

It would be fairer to say that this is a book about the times in which Charles Todd spent his early life. In the first chapters, we are given some background information on Regency and early Victorian England and introduced to Charles Todd as he is employed by the Royal Observatory, Greenwich. Soon, however, Todd disappears from the narrative as we are given long descriptions of early Adelaide. Finally, he reappears in the last chapter as he starts to make his technological contributions to Australia.

Early Adelaide

The authors devote much of the book – four chapters out of nine and about half the pages – to describing Adelaide in its early days, before the Todds arrive. They make much of the disorganization and misrepresentation of the South Australian Company (the founding institution) and the early colony. For this description, the authors are perhaps overly dependent on the work of Henry Hussey, an early immigrant who left several accounts of his life and times. They also seem to take particular exception to George Fife Angas, a major figure in the founding and promotion of the colony. Surely he was no better or worse than many a Regency businessman.

The authors also take a rather prurient interest in the seamier side of Adelaide life, devoting most of a chapter to sexual scandals and evidence before the magistrates of brothels and sly-grog shops. While this is colourful, it seems to have little to do with Todd. Are the authors hinting at some such episode in Charles Todd's life? We are not told. Indeed, the evidence is rather that Todd was devoted to his wife, Alice (after whom he named Alice Springs).

While all this is diverting for the reader, especially for South Australians, it is only glancingly relevant to Todd. As the authors themselves say, the colony was set on a new path after the commencement of copper mining and the end of the first gold rushes in Victoria in the late 1840s. By the time the Todds arrived in late 1855, almost 20 years after the colony's foundation, Adelaide and its environs were well on the way to being the prosperous and well-ordered place we all know today.

Charles Todd and his achievements

So, what do we learn of Charles Todd and his early achievements? We learn of his first employment at the Greenwich Observatory and his relationship with the Astronomer Royal, George Airy. We learn of his outposting to the Cambridge Observatory (where he met his future wife) and his introduction to the electric telegraph, which ran between the two establishments.

Todd returned to Greenwich in 1854 to head the 'Galvanic Department', which looked after the telegraph lines and their power supply (batteries). Although he was not in the post long, he gained valuable experience in maintaining a telegraph system when he worked on fixing the automated time-keeping system at Deal on the Kent coast, kept synchronized to Greenwich by a telegraph line of about 150 km. (Part of the problem was a 'weak wire' at Tonbridge.)

When Todd arrived in Adelaide, he brought with him material for building a telegraph line between Adelaide and its port, a distance of about 14 km. He had the line working within a few months. In fact, it turned out that he had sufficient material also to build a later line to Gawler, a further 40 km. The controversy about the expense of Todd's early activities and the competition with a 'commercial' line, which was already operating to Port Adelaide, is briefly described in the book.

The book ends with an account of Todd's visit in 1856 to Sam McGowan, roughly his opposite number in Melbourne. Together, the two men promoted the idea of electric telegraphs between the colonies, first between Adelaide and Melbourne and later between Melbourne and Sydney. This was the beginning of the activity that led to the inclusion of telegraphy and telephony within the Postmaster General's Department at Australian federation.

Strangely for a book published by the Australian Meteorological Society, we are told little of Todd's activities regarding the weather and weather forecasting. These were of great importance to South Australia and other colonies in the time leading up to Federation. We are told that Todd checked the calibration of temperatures then recorded in Adelaide – no problems were found. We are also told that Todd, like others, believed that the telegraph could be used to collect weather data from a wide area and hence assist in prediction. But there is not a hint of Todd's great legacy, the weather records and synoptic charts kept meticulously from 1879, now considered one of the gems of Australian colonial science.

Conclusion

Charles Todd was a great pioneer in the establishment of the electric telegraph and weather records, and, importantly, in the management of both, in Australia. His life and achievements should be widely known and celebrated.

The present book is a footnote to Todd's life. It gives some background, often diverting, about the influences and attitudes that would have, or could have, shaped Todd's early experiences, but it largely misses the mark about Todd himself. For a true understanding of Todd, the reader should look elsewhere.

Reference

Rogers, Tony & Ferrante, Judy. 2017. *The Weatherman from Greenwich: Charles Todd – 1826 to 1910*, Adelaide: Australian Meteorological Association.

A Historical Perspective on WRESAT, the First Satellite Launched from Australian Soil

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Abstract: Just over fifty years ago, on 29 November 1967 at 2:19 pm (local time), a small scientific satellite named the **W**eapons **R**esearch **E**stablishment **SAT**ellite (**WRESAT**) was launched from Woomera, South Australia. It had been designed and constructed by engineers, scientists and technicians from the Weapons Research Establishment, Salisbury, South Australia; it had a payload of scientific instruments put together by the Physics Department at Adelaide University; and it was sent into orbit at the sharp end of a modified Redstone rocket, a gift from the United States. All of this was achieved in less than 12 months; and it made Australia the third country in the world to launch a satellite into space from its own territory, after the USSR and the USA. This paper is the author's personal account of his part in the project, where he was involved first with the satellite's telemetry system and then with a temporary extension to Oodnadatta of Woomera's flight safety system. The paper goes on to describe events following the successful launch, and the celebration of the 50th anniversary in 2017. Finally, there is a discussion of the politics and technologies behind WRESAT.

Keywords: Satellite, WRESAT, Telecommunications, Woomera

Introduction

This paper provides a review of the history of the launch of Australia's first satellite and how it came to be. This was an exciting time for Australia's new space and electronics industries and the satellite launch highlighted the successful partnership between Defence and the University of Adelaide.

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Recruited into Telemetry

In the mid-1960s, I was a recently graduated electronic engineer and I had found work in the Telemetry Systems Group at WRE Salisbury – the former Weapons Research Establishment, situated near Salisbury, South Australia. Over the years WRE has evolved into the present-day DST Group Edinburgh.

Telemetry can be described as the automatic measurement of things remote or inaccessible, and the transmission of the measurements to a device for recording or display; and in this case, the things remote or inaccessible were generally attached to missiles undergoing flight trials at Woomera. Here is a very brief outline of how the telemetry used to work when I first joined the group:

- During a missile trial, the voltage levels from a few dozen measuring instruments attached to the missile were time-multiplexed into a single data stream, and the data stream was sent back to the range instrumentation centre by UHF radio.
- At the instrumentation centre the received data was demultiplexed to provide quick-look records, for the benefit of missile contractors and others who were anxious to see what might have been happening during the trial.
- The raw multiplexed data was tape recorded, and the tapes were sent to Salisbury for data reduction and analysis.

Among the staff of the Telemetry Systems Group there were electronics specialists who spent their days maintaining and improving the technologies and procedures being employed in telemetry at both Woomera and Salisbury; and I was able to learn something of their craft when I joined them in one of the labs.

We Were Going to Launch a Satellite!

In January 1967, the word got around that WRE was going to build a satellite and launch it from Woomera — which sounded quite interesting.

A very secret lot of trials called Project Sparta had been under way and most of us didn't have a clue what it was all about, because we had no need to know. Security was pretty strict and effective back then when the Cold War was at its hottest. We now know that, under a tripartite agreement, a team from the US, the UK and Australia had been launching modified Redstone rockets in near-vertical trajectories to find out what happened when warheads or spacecraft re-entered the atmosphere at enormous velocities. The Redstone was a liquid-propellant rocket with a very good reputation for reliability, and a few years previously it had been used in Project Mercury to launch first monkeys, then the first seven American astronauts, into space. With second and third stages fitted, one of these rockets would stand about 22 metres tall.

For the Sparta project, a batch of ten modified Redstone missiles had been sent over from the US and, with the success of every one of the nine planned launches, there was a spare launch vehicle just lying there, unused.

Australians high up in the Defence hierarchy had a few ideas about how this rocket could be used, and their hints were not terribly subtle. After all, mate, if it's going to be shipped back to America, it will probably just end up on a scrap heap, won't it? Well, the Americans gave us the spare Redstone; they gave us the services of the launch team; and they undertook to have the inertial guidance system reprogrammed for a satellite launch. Our masters in Canberra found some petty cash to pay for building and launching a satellite – it would be a nice, cheap way of gaining some international prestige, and there might even happen to be a few spin-offs for Australian science and defence.

The satellite was going to be called the Weapons Research Establishment Satellite (WRESAT). The goals could be summarised as:

1. To extend the range of scientific data relating to the upper atmosphere;
2. To assist the US in obtaining physical data of relevance to its research program;
3. To develop techniques relevant to the launching trials in the ELDO (European Launcher Development Organisation) and British satellite programs;
4. To demonstrate an Australian capability for developing a satellite using advanced technology and existing low-cost launch facilities at Woomera.

It didn't take long for the project to get under way. People from all over WRE, myself included, found themselves contributing to the project from time to time and then going back to ordinary work. The satellite itself was being designed and built by WRE and the experiments going up in it were being provided by the Adelaide University Physics Department, where there was a long history of upper atmospheric research using locally developed rockets.

Telemetry for WRESAT

The basic NASA system

My particular contribution to the project started at one of the Telemetry Systems Group meetings, when I was handed a NASA booklet with a title that went something like 'Telemetry Format for Small Scientific Satellites'. I was asked to study this document, have some thoughts about what could be done for WRESAT, and report back.

The booklet described the signal processing steps to be followed when you had a few dozen instruments on board such a satellite and you wanted to transmit the measurements back to earth for subsequent data analysis. It didn't take me long to see that the NASA telemetry system had a lot in common with the one we were using at Woomera and which I had come to understood in some detail. The two systems used the same modulation techniques for data multiplexing, encoding and transmitting, and the main differences could be described in terms of some scale factors. By scaling the number of data channels, a few encoding parameters and the downlink frequency, you could, in theory, have converted Woomera telemetry to NASA telemetry, or NASA telemetry to Woomera telemetry.

At that time, NASA had a system called STADAN, the ‘Spacecraft Tracking and Data Acquisition Network’, which received, recorded and processed telemetry data from an experimental satellite and calculated the satellite's orbital parameters. In addition, universities and other research organisations around the world had their own NASA-compatible satellite receiving stations and they were prepared to tape record other people's raw telemetry data and send the tapes back to the experimenters by courier or parcel post.

The Woomera ‘Type 465’ telemetry…

The system being used at Woomera, and with which I was now familiar, had been developed in the 1950s at the Royal Aircraft Establishment, Farnborough, UK. It was called ‘Type 465’, presumably because it transmitted on a nominal frequency of 465 MHz.

A telemetry kit on board a missile included a small electric motor, called a switch motor, spinning around at about 50 revolutions per second, to drive a simple 24-segment commutator. Twenty-three of the commutator segments, for data channels, were connected to measuring instruments such as strain gauges and accelerometers; and the 24th segment, for the sync channel, was connected to a special DC voltage that would stand out like a sore thumb from any of the sampled data voltages.

The common signal output from the switch motor was sent off to a frequency-modulated subcarrier generator, to produce subcarrier frequencies varying over the range 130 to 160 kHz for the data channels and fixed at 180 kHz for the sync channel.

The subcarrier then amplitude-modulated the missile's nominally 465 MHz UHF signal; and the amplitude modulated UHF signal was transmitted to receivers on the ground.

At the range-head instrumentation centre, the frequency-modulated subcarrier was detected, and tape recorded for analysis back at Salisbury. For the quick-look displays required by technical and contractor personnel, further processing was performed in real time to extract instrument readings and send them off to display devices such as chart recorders.

Until early in the 1970s, the active components of a missile's telemetry equipment would generally have been designed around thermionic valves and electromechanical devices. By the standards of the day, it was described as sub-miniature. To stop the batteries from going flat during pre-launch preparations, a missile would be connected to an external 'shore' power supply until just before launch; and after launch, battery drain would not be such an issue because of the missile's very limited life expectancy.

Telemetry parameters for WRESAT

The satellite telemetry system described in the NASA booklet transmitted in the 136-138 MHz band — which is still being used for satellite telemetry but with frequencies below 137 MHz now deprecated.

As with the '465' telemetry system:

- The data voltages from multiple and independent data channels were time-division multiplexed into a pulse-amplitude-modulated data stream, with a unique data voltage set aside for the sync channel.
- The time-division multiplexed data was used to frequency modulate a subcarrier.
- The transmitted VHF radio signal, in the 136-138 MHz band, was amplitude modulated by the subcarrier.

When I studied the booklet's signal parameters I came to the conclusion that the design was quite conservative and I was certain that I could make better use of the available bandwidth. With some tweaking of the number of channels, the sampling rate and the subcarrier frequencies, I arrived at a compatible alternative design offering a tenfold improvement in data collection rates and without compromising data accuracy. I can't remember the exact details of what I designed; but I think there were about 20 channels, each sampled about 20 times a second. The details might be buried in a research paper somewhere.

It wasn't long before I was told that my design had been accepted and that the details had been passed on to the satellite instrumentation contractors in the United States.

The WRESAT Ground Station

I was asked to go ahead and develop some ground station equipment that would give us an idea of what was going on in our satellite while it was up there in orbit. What we needed was something that would take the telemetry subcarrier coming in through a VHF radio receiver, demodulate the subcarrier to give a copy of the sampled data stream, and then demultiplex the data stream to recover instrument readings. Watching what was happening in real time on an oscilloscope would give an indication of whether the satellite and its instrumentation were still in good health.

The first step towards developing the ground station was putting together a sort of bench-top satellite simulator – an assembly of electronics that produced a frequency modulated subcarrier, driven by a repetitive stream of pulses representing the output from a sampling switch. The thing was no joy to behold, but it did the job.

My design was based on current, state-of-the-art electronics – which, at the time, involved components such as matched pairs of silicon transistors, and inductors wound on special ferrite cores, all of it soldered onto circuit boards with connecting wires at the back and plugged into a card tray. For some parts of the ground station, I was able to call on existing designs from our 465 telemetry replay equipment and, for other parts, I had to work it out for myself, more or less from first principles.

It took about six weeks, with a fair bit of overtime, to get all of this to a state where a draughtsman could produce detailed drawings. A radio tradesman assembled the final product into a neat and professional-looking bench-mounted box and it worked perfectly.

What Other Groups Were Doing

As the months went by, we shared our snippets of WRESAT news around the tea trolley. Here are some of the things we were hearing about and discussing:

- The mechanical engineers had received the design requirements for fitting a satellite to a Sparta vehicle. They had designed and built a model of the satellite and had performed spin tests to determine its dynamics – because when the satellite reached orbit, the experiments required it to be spinning at a particular rate and on a particular axis.
- The satellite model had been subjected to vibration testing – I think it was something like 30 or 40 G at frequencies up to about 20 Hz. You don't want a satellite's bits and pieces rattling around inside while it is being launched.
- The satellite and its instrumentation were being put through extensive laboratory testing.
- The radiation pattern of the telemetry aerials had been measured out in the Aerial Test Field.
- Explosive bolts had arrived. They were going to secure external panels and the nose cone during launch; and when the satellite reached orbit they would pop to jettison the panels and nose cone and expose the experiments.

And in between WRESAT work, most of us continued with our more normal activities.

Range Safety for the Launch

The requirement

In August 1967, I temporarily joined the team responsible for WREBUS, the Weapons Research Establishment Breakup System. It was a part of the flight safety system that blew up missiles when they strayed off course or got out of hand. During a missile flight trial, the Range Safety Officer kept an eye on where the thing would impact if its propulsion system were to cut out; and if the predicted impact point came too close to the edge of the designated safety corridor, he pressed his Big Red Button; coded radio signals were transmitted to the missile; and a small explosive charge was detonated to break it up, with the debris coming down inside the safety corridor.

Because radio waves can be severely attenuated when they pass through a rocket's exhaust plume, the WREBUS system at Woomera was equipped with two separate transmitters, separated geographically and separated in frequency, but transmitting identical codes. This was to ensure that a missile would always be able to receive the codes, regardless of its heading. The missile's receiving system listened simultaneously on both frequencies; and if reception on one of the frequencies faded away because of flame attenuation, there would still be good reception on the other frequency.

But with the WRESAT launch there was a problem – when the second stage motor ignited, up in the sky and far away, the exhaust plume was going to cut off the signals from both transmitters back at the launch site. It was a matter of simple geometry. So a third transmitting station was needed at a location well away from the exhaust plume's line of fire. The chosen spot was Oodnadatta, and two WREBUS transmitters, one for each frequency, were going to be installed in a portable caravan located next to the airport runway.

The Oodnadatta WREBUS station had to be integrated into the Woomera range safety system and controlled remotely from Woomera It had been decided that the most practical way of achieving this was to send control signals between Woomera and Oodnadatta simultaneously over a landline and two shortwave radio channels. Sending the same signals simultaneously over three separate and independent channels would improve reliability.

The distance from Woomera to Oodnadatta is about 410 km as the crow flies. The two chosen radio channels were normally used for voice communication between Woomera and the Giles weather station in Western Australia, and they wouldn't pose much of a technological problem apart from the inevitable noise, interference and fading that's to be expected with high frequency ionospheric radio. But the landline was another matter. Telephone lines through the bush between Woomera and Oodnadatta might have existed, but you really can't use party lines strung between gum trees in a prime safety system. So the PMG's Department did their best for us by patching together a 6000 km detour along the nation's trunk telephone network. It went south from Woomera to Adelaide; eastwards across Victoria; up the coast, probably as far as Rockhampton; inland across Queensland and the Northern Territory to Tennant Creek; and south through Alice Springs to Oodnadatta. At Oodnadatta it took out one of the three lines going into the town, to leave only two lines between Oodnadatta and the outside world.

In the Instrumentation Building at Woomera there would be a pair of wires coming from the Safety Officer's push button; and at Oodnadatta there would be another pair of wires going to the WREBUS transmitters in the caravan. My job was to put together some electronics that would behave like a solid, reliable, 410 km long pair of wires joining the Woomera push-button to the Oodnadatta transmitters. For this, I had to use a combination of two channels of high frequency ionospheric radio, which is a technology notoriously subject to noise, interference and fading, along with a ridiculously long landline, which also could be prone to noise and interference but hopefully not to the same extent as the radio channels.

Signalling by wire and wireless

I spent a few weeks in the lab trying out some ideas. When I had a working prototype the circuit diagrams and construction details were drawn up by a draftsman and a radio tradesman did a very nice job of putting it together. It all fitted into two small bench-top equipment cabinets, one of them for the Woomera Instrumentation Building and the other for the Oodnadatta caravan.

I had devised a scheme in which the current state of the Safety Officer's button was sent over the link in short coded messages, repeatedly and continuously. There were just two messages, which I called respectively ‘Prohibit’ and ‘Fire’. ‘Prohibit’ was sent out over the link four times a second while the Safety Officer's finger was away from the button; and ‘Fire’ was sent out two times a second while the Safety Officer was pressing the button. English translations of the coded messages would have gone something like this:

- **Prohibit** – ‘The Range Safety Officer is not pressing the button, so please refrain from keying the transmitters on for the next 2 seconds’.
- **Fire** – ‘The Range Safety Officer is now pressing the button, so please key the transmitters on immediately and destroy the missile’.

The ‘Fire’ message code was twice as long as the ‘Prohibit’ code, and more complex, because receiving and decoding a false ‘Fire’ command would have had much more serious consequences than receiving and decoding a false ‘Prohibit’ command.

I transmitted the message codes using three electrical signalling levels – two levels to carry binary data for 'Prohibit' or 'Fire', and the third level to provide clock pulses for the shift registers used in the decoders at the Oodnadatta end. I figured that the decoders might need all the help they could get as they struggled to detect recognisable patterns among the interference and other rubbish coming in over the air waves and the telephone system. I had a feeling that a phase-locked loop might keep dropping out when the going got rough.

At Woomera, the three-level pulse stream generated from the state of the safety button was fed to a frequency modulator, to produce an audio-frequency subcarrier occupying a band of about 300 Hz to 3000 Hz – this made it compatible with voice communication plant. The subcarrier was then sent on its way, simultaneously, over the two high frequency radio channels and the 6000 km landline.

At Oodnadatta, the signals coming in over each of the three channels were examined individually and independently, to see whether there might be any 'Prohibit' or 'Fire' message codes detectable among the noise and interference. For each channel the received signal was sent to a frequency demodulator, or discriminator, to produce what would hopefully be a filtered three-level pulse train. If the signal amplitudes from the demodulator fell within acceptable limits, clock pulses were extracted to move the demodulated binary data through a system of shift registers, and logic gates detected the presence or otherwise of 'Prohibit' and 'Fire' codes. Whenever a valid code was detected, the appropriate control line feeding to the transmitter system was latched to its 'Code Received' state; and if another code of the same type was not received within a certain time interval – 2 seconds for 'Prohibit' codes – the latch would be automatically reset to its 'No Code Received' state

Until the transmitters were armed and ready, the terminal equipment at Oodnadatta would be doing little other than working away at receiving and decoding signals coming in by radio and landline. It had a display panel with lamps to show the status of the three communication channels and there was a loudspeaker to let you hear what was coming through on the radio channels and the landline. The loudspeaker was also part of an intercom that could be switched into the landline back to Woomera, temporarily interrupting the flow of message codes.

The transmitters remained disabled until the officer in charge armed them with keys that he otherwise kept safely in his trouser pocket; and once armed and ready, the transmitters gave ample warning of their status with buzzers and flashing lights. It was all quite dramatic.

With the transmitters armed and ready, the only thing that could stop them from going on air was the continuous arrival of 'Prohibit' codes no more than two seconds apart. They were being sent from Woomera at the rate of four a second, simultaneously over three channels; and if conditions were to deteriorate to the extent that nothing recognisable could be decoded at Oodnadatta for more than two seconds straight, it would be an indication that the overall link had failed and the transmitters would be keyed on automatically to destroy the missile. This was in line with the mandatory fail-safe policy for this sort of safety system. If ever control of the command breakup system were to be lost during a flight trial, the system had to take over automatically to cut the missile down and avoid the risk of having it stray outside of the safety corridor.

And when the transmitters were armed, a single 'Fire' command coming in over a single channel would be sufficient to key the transmitters on and destroy any WREBUS-enabled missile within radio range.

I knew I had to get the design right.

Installation and Field Testing

A lot had to be done ahead of the launching and a team of about half a dozen of us spent various amounts of time at Oodnadatta to set up all the gear and check it out. When I arrived for my stay of about two weeks, the radio masts were up and the caravan was in position and largely operational. Over several weeks of field testing, sometimes with severe interference on the radio channels along with crackling and cross-talk on the telephone line, the link from Woomera to Oodnadatta didn't fail a single time. Every 'Fire' command sent from Woomera was received promptly and there were no dropouts lasting long enough for a failure event to be triggered.

Designing, building and commissioning the Oodnadatta station had taken us only 10 weeks.

The Satellite Launch

Countdown preparations

About a week before the scheduled launch date I had to travel to Woomera, where I was to be the WREBUS operator at the Woomera end of the link to Oodnadatta.

The Woomera part of my equipment had been installed on a bench in Room 4, the Hazardous Circuits Room of the Woomera Instrumentation Building. The room had racks full of equipment associated with the launching of missiles, and it was the domain of two highly reliable and experienced operators. During any trial the door was kept locked from the inside to guard against any interruption or interference. That's where I would be stationed for the WRESAT launch.

Figure 1. WRESAT on the launch pad (Source: DSTO 2018)

I was given a copy of the trial instructions for the WRESAT launch – it was a long document with a numbered list of the many actions and procedures to be followed during the count-down. In the days leading up to the launch there were several rehearsals and anybody with a part to play, including the Oodnadatta crew, had to be standing by, ready to respond over the intercom network whenever the count-down reached an item for which he or she was responsible. The intercom between Woomera and Oodnadatta was connected over the 6000 km landline, and the terminal box at each end of the line had a switch for manually swapping between data transmission and intercom. The count-down involved a lot of systems, subsystems and personnel – there must have been a cast of hundreds – and a summary of systems would have included launch vehicle preparation, payload preparation, telemetry, range safety, optical tracking, radar tracking, and more.

The count-down rehearsals were conducted at quite a rapid pace, and in some parts of them hours of count-down time were compressed into just minutes of rehearsal time. But the real count-down on the day of the launch was to start, as I recall it, at about 4 in the morning, and keep going until ignition and lift-off at about 2:19 in the afternoon.

During the rehearsals, my own small parts in the count-down had me acknowledging that I was present at my post in Room 4, and that my end of the link to Oodnadatta was working. And when the Oodnadatta crew received their cues over the intercom, they were able to acknowledge that they were present, that the link was working normally at their end, and that their transmitters were operational and standing by.

When the time came for the satellite to be mated to the launch vehicle, the Americans were horrified when they saw it being brought along on the back of a ute. They were used to keeping payloads like that wrapped in cotton wool until the last minute. The Australian response went something like: ‘Well, if it has to survive a ride on top of that monster of yours, we reckon a ride on the back of a ute isn't going to do it too much harm’.

The launch was supposed to take place on Tuesday, 28 November; but the countdown on that day had progressed to less than a minute before ignition when there was a call of ‘Stop Stop Stop’ and the trial had to be aborted. An air-conditioning unit had failed to detach from the upper parts of the missile.

Ignition, Liftoff and Orbit

On Wednesday, 29 November 1967, everything went smoothly. As set down in the Trial Instructions, when the countdown reached zero and I heard the announcement of ‘Ignition’ over the public address, I repeated ‘Ignition’ over the intercom to Oodnadatta and I received their acknowledgement. Then, at +23 seconds and right on schedule, I heard and repeated the announcement of ‘Lift Off’.

Oodnadatta acknowledged Lift Off, and at both ends we switched the landline from intercom to data. My ‘Prohibit’ commands started flowing from Woomera to Oodnadatta. At Oodnadatta, keys were turned in locks to arm the transmitters; and after the designated time interval, the transmitters were disarmed again. We crossed our fingers, waiting to see what was going to happen.

Back at Woomera we were being given a running commentary over the public address as the launch progressed. About 6 minutes after lift-off we were told that WRESAT was in orbit. I got onto the Oodnadatta intercom as soon as I could to tell them the news, and I think I sounded more than a bit excited.

A hundred minutes later, at around 4 o'clock in the afternoon, I was standing next to my ground station equipment in the Instrumentation Building, watching telemetry data coming in from WRESAT. Our satellite was a few thousand kilometres away over the Indian Ocean, off the West Australian coast near Carnarvon, and it was heading towards the North Pole at the start of its second orbit.

A short excerpt of a documentary that includes the WRESAT launch is available on YouTube (2012).

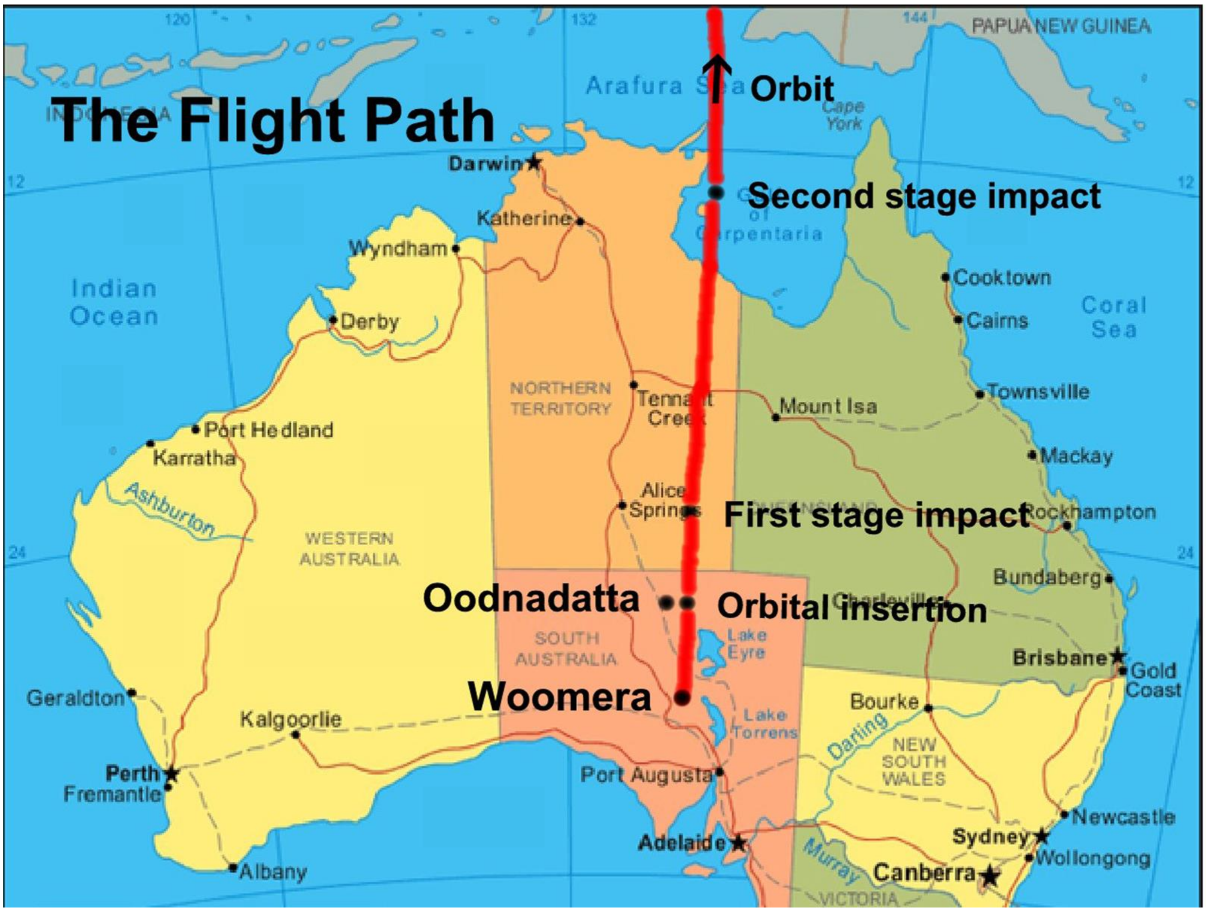

Figure 2. The WRESAT flight path

That night we had a tremendous party back in the Woomera Senior Mess. I'm afraid I was one of the young fellows at the back of the hall, from where we were carrying on with great glee and gusto while a succession of VIPs up front were doing their best to congratulate us all.

Until one of the satellite's batteries went flat four-and-a-half days later, a bit sooner than expected, ground stations from all around the world kindly recorded WRESAT telemetry signals for us and sent us their tapes. I wonder how many PhDs were generated from that data?

WRESAT re-entered the Earth's atmosphere on 10 January 1968, after 43 days in orbit, and it burnt up over the Atlantic Ocean to the west of Ireland. In 1990 the wreckage of the Redstone first stage was found in the Simpson Desert. It was returned to Woomera, where it is on permanent display.

In the News

For a week or so after the launch, news about WRESAT was hitting the headlines world-wide. Australia had joined the USSR and the US to become the third country in the world to design and build its own satellite and launch it from its own soil. This had been achieved in the impressively short time of eleven months, and it had placed Australia among the world leaders in space technology.

Work associated with WRESAT continued sporadically for a few more months with meetings, reports, papers and presentations. Such was the interest in space technology that the WRESAT prototype was exhibited in Parliament House, Canberra; then at the London Trade Fair in 1968; and in various museums and galleries around Australia.

Here is my unofficial assessment of the project's achievements, in the same order as the list of project goals:

1. The range of scientific data gathering, relevant to the upper atmosphere, had been extended, to the extent that data collected during 4½ days of low-earth orbit would have augmented similar data collected by high-altitude sounding rockets.
2. This small battery-powered satellite could not have contributed very much to the massive US research program, when data could be collected for only 4½ days.
3. During preparations for the WRESAT launch it had been shown that it was safe to carry a small conical satellite to its launch site on the back of a ute. Would this be seen as a technique relevant to the launching trials in the ELDO and British satellite programs?
4. WRESAT had indeed demonstrated an Australian capability for developing a satellite using advanced technology and existing low-cost launch facilities at Woomera.

Fifty Years Later

The Australian Government had for fifty years shown no interest in developing a home-grown Australian space industry, and WRESAT had no successor. The only other satellite launched from Australian soil was Prospero, a British research satellite launched from Woomera in 1971 using a Black Knight rocket. While there have been other Australian satellites that were designed and built in Australia, they have not been actually launched from Australia.

Then, in September 2017, the Government expressed a renewed interest in space exploration. During the 68th International Astronautical Congress held in Adelaide, it was announced that Australia would create its own space agency in an attempt to cash in on a $420 billion aeronautical industry, and it would create thousands of new jobs. Australia was the only OECD country without a space agency.

To coincide with the Astronautical Congress, an exhibition of space-related memorabilia from Woomera had been set up in the State Library of South Australia, with an emphasis on high-altitude sounding rockets and WRESAT. In one of the glass cases, there was a prototype of the WRESAT telemetry encoder, constructed from rectangular pieces of perforated fibreglass board and bolted together into an assembly about the size and shape of a loaf of sandwich bread. The topmost circuit board had a row of rather large, gold-plated, antique, integrated circuits, and the other boards were packed with electronic components and neat bundles of wiring. Nowadays, the same functionality could be designed and built into a single chip the size of a postage stamp.

Officials from the Department of Defence in Canberra had managed to track down just a few of the original WRESAT team, from other organisations as well as from WRE, and had invited them to a special 50th anniversary celebration at the State Library of South Australia. It was to take place while the Astronautical Congress was still in progress. The event was held in a lecture theatre next to the space exhibition, and the WRESAT veterans were greeted by Members of Parliament, the Chief Defence Scientist, and other notables. After some speeches, the veterans were paraded one by one to be presented with souvenirs that included a framed certificate and a medallion. Afterwards there were some interviews with the ABC: excerpts from the interviews kept popping up in radio documentaries and news broadcasts for several weeks.

The Significance of WRESAT

What is the overall significance of WRESAT? The principal motive for building an Australian satellite and launching it from Australia must have been political, with the aim of gaining international praise and prestige. The amount of scientific data to be collected would have been of secondary importance, but it was important that WRESAT be seen as a real scientific satellite. A goal like 'Assist the US in obtaining physical data' must have been more about politics than science. When it was a success, Australia suddenly joined the world leaders in space technology, but was quickly overtaken when the government showed no further interest. WRESAT was virtually forgotten for nearly 50 years, until some old hands lobbied successfully for its memory to be revived in a series of celebrations. WRESAT is a memory of a short-lived glorious past, with little relevance for the present or the future except as an inspiration to show what might be achieved.

The activities and outcomes from WRESAT hold little continuing value:

- Significance for science: Little. In the overall scheme of things, the quantity of data collected was very limited because of the limited life of the batteries. The data probably would not have added significantly to any extended statistical database of the phenomena being observed.
- Significance to the development of rocketry: None. The launch vehicle was of a mature design and very reliable.
- Significance for the development of telemetry: None. There was nothing revolutionary in the telemetry system: it was just the application of a few scale factors to a generic design. Over the years the technologies and data encoding schemes for satellite telemetry have changed enormously. NASA now has readily accessible websites

offering a lot of useful information, some of it in tutorial form, for anybody wishing to design a telemetry system, for almost any type of spacecraft, and for almost any type of space mission.

- The Woomera-to-Oodnadatta control link. With the high-quality telecommunication services now in place across most of Australia, setting up a reliable control link across a few hundred kilometres of the Australian bush should never again require such an eclectic mixture of borrowed shortwave radio channels, thousands of kilometres of landline patched together from the national telephone network, and a paranoid coding scheme.

Conclusion

This paper has described just two of the technical challenges that were overcome to make WRESAT a success. In the big picture of space exploration, WRESAT was a one-off, opportunistic adventure into space technology that turned out to be successful. Apart from serving as an historical case study and an inspiration to show what can be achieved, any experience gained fifty years ago would have very little impact on an Australian space industry in the 21st century.

But it was fun while it lasted.

References

DSTO. 2018. WRESAT — Weapons Research Establishment Satellite, DST Group, March 2018. Retrieved from https://www.dst.defence.gov.au/innovation/wresat-%E2%80%94-weapons-research-establishment-satellite

YouTube. 2012. Weapons Research Establishment Satellite (WRESAT), 1967, National Archives of Australia, 24 April 2012. Retrieved from https://www.youtube.com/watch?v=Or5dyDmBq_I

http://doi.org/10.18080/ajtde.v6n1.144

Australian Broadband Regulation Reviewed

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Abstract: This article establishes the relationship between the condition of Australian broadband services and Australia's history of broadband regulation. It briefly surveys the history of the industry in terms of government action and firms' responses. It reviews research on the effects of regulation and industry concentration internationally, which indicates that the effects of widely deployed policies are often small or undetectable. The article uses these findings to build models of national broadband prices, penetration and quality. The models are verified using recent statistics from developed economies, confirming that outcomes are little affected by access regulation, and also not by market concentration. Penetration and quality are strongly affected by technology factors. The models and the regulatory history are used to explain the condition of Australian broadband services, and to extract lessons applicable to future policy development.

Keywords: Broadband, Australia, Regulation, Market power, Network technology.

Introduction

Australian regulation of fixed broadband networks was broadly consistent with other developed economies until 2009, when NBN Co was established as a government-owned monopoly. Australian consumers are currently less satisfied with Internet services than with mobile phone or fixed line telephone services, and are particularly dissatisfied with Internet data speeds, service costs and the speed of fault repairs (ACMA 2017, pp. 60-61). Successive government policies are regularly criticised as contributing to poor Australian outcomes, but how much impact does policy actually have, compared to the impact of other economic and demographic factors?

This article explores this question through an international comparison. It reviews Australian policy across the era of broadband Internet, and then reviews research about the impact of such regulation internationally. Models of broadband pricing, penetration and quality are formed by applying this research to recent data from developed economies. These models are used to explore Australian broadband outcomes, and to trace the effects of regulatory policies and decisions. Implications for future broadband policy are also discussed.

http://doi.org/10.18080/ajtde.v6n1.131

History of Australian Broadband Regulation

Ownership separation, competition and intermediate compromises have been features of Australia's telecommunications regulatory policy for decades. Ownership separation refers to detaching the ownership of monopoly infrastructure from the ownership of firms using that infrastructure to deliver services (Baldwin, Cave & Lodge, 2011, p. 467). Ownership separation, referred to as structural separation, is the solution currently adopted in Australia (Telecommunications Act, 1997). It was adopted after long experimentation with other remedies for market failure, including competition and functional separation.

In the late twentieth century, competition, initially in long distance and international calls, was preferred to monopoly regulation of Australian telecommunications. Such competition would "encourage the expansion of Australia's telecommunications infrastructure and industry" (Brown, 1990). Enabling this competition initially required regulated access to Telecom Australia's (later Telstra's) local network, and AUSTEL was established as an industry regulator (Telecommunications Act, 1991). Beginning in 1997, the need for public oversight increased as Telstra was privatised in three stages (Telstra (Dilution of Public Ownership) Act, 1996). Over time, competition in telephony expanded to include infrastructure, when Optus and Telstra constructed rival hybrid fibre coaxial (HFC) networks, carrying pay TV alongside telephone calls. And as networks were expanding, new applications were emerging, notably the Internet (Richardson, 1997).

Internet access, especially email and the World Wide Web, emerged as a significant third use for telecommunications networks in the 1990s. Dialup Internet protocol (IP) services could be delivered to households over the existing (copper or HFC) networks, with new equipment required only on the customers' and the Internet service providers' (ISP) premises. Dialup Internet services had limited bandwidth and could not be used concurrently with telephone calls. HFC networks offered superior Internet access and enabled the "triple play" of telephone, pay TV and Internet services to utilize and repay the investment in HFC infrastructure. But accessibility and low cost meant dialup remained the most common mode of Australian household Internet access until 2006 (Figure 1). For households without HFC access, the alternative to dialup was a digital subscriber line (DSL) service delivered over existing copper telephone lines. DSL had at least 17 times the bandwidth of dialup services, up to 1500 kbps, and bandwidth increased further as technology improved. Increasing bandwidth over the copper network enabled Internet services such as video streaming, multiplayer computer games and file sharing, without significant new network construction.

Without overbuilding, entrepreneurial ISPs could only resell services delivered over Telstra's monopoly copper network. They could not easily compete with Telstra's and Optus's vertically integrated products, and captured little DSL market share. Figure 1 shows the initially high but rapidly falling retail market share (as percentage of total subscriptions) of dialup access from 2005. Telstra and Optus combined had 90% of retail broadband (DSL and HFC) subscribers in 2007. (In accordance with the Australian Bureau of Statistics, broadband here is defined as “an 'always on' internet connection with an access speed of 256kbps or higher” (ABS 2017).) iiNet was the most successful start-up with only 6% of subscribers. Competition was not thriving.

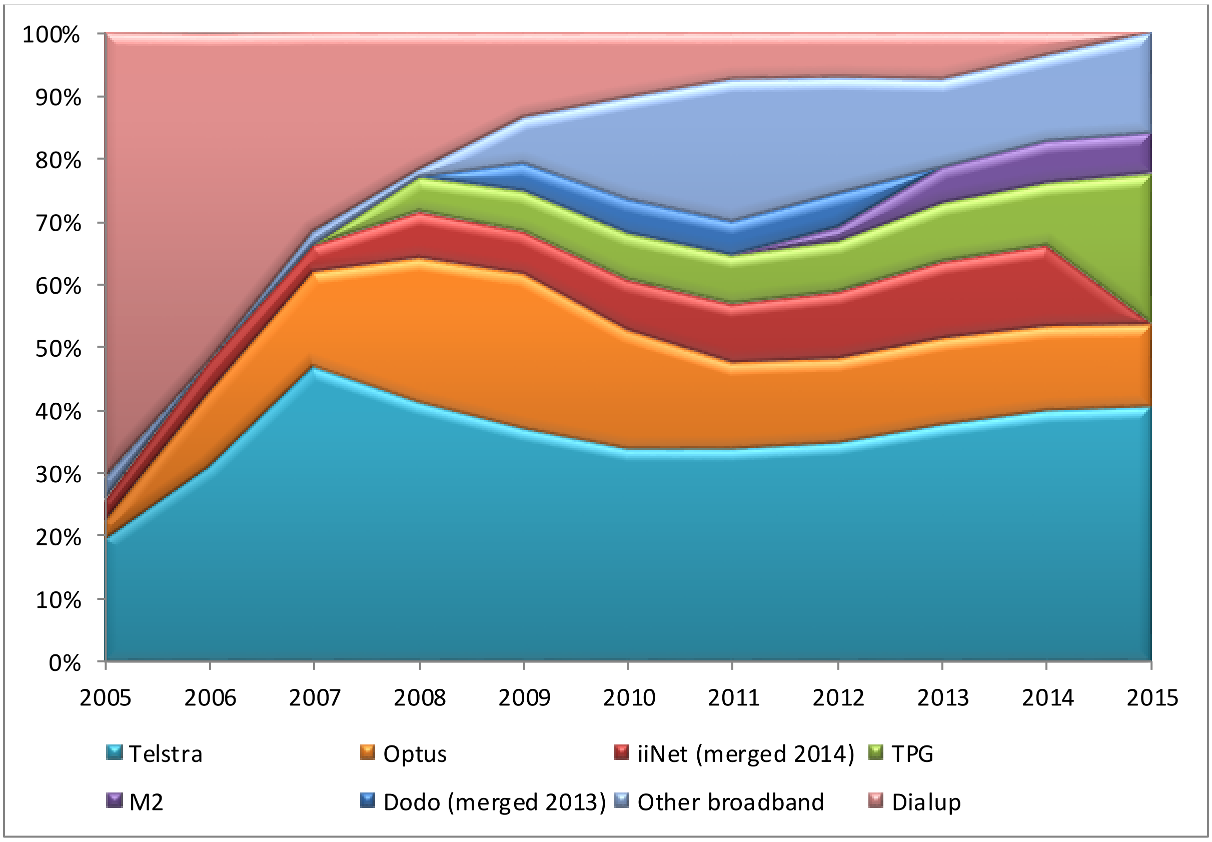

Figure 1 – Subscriber concentration in the Australian residential Internet market. Company and Other broadband shares are given for broadband subscriptions according to the ABS definition, dialup subscriptions are consolidated. (Source: Author's calculation from ABS data and companies' public reports and investor presentation)

Australian law gives the Australian Competition and Consumer Commission (ACCC) authority to “declare” certain telecommunications services, that is, to establish regulated access to declared services (Telecommunications Act, 1997, Clause 350A). Telstra's local line monopoly concerned the ACCC, and various Telstra operations were declared in 1997, which allowed other firms to access Telstra services on a wholesale basis at set prices (ACCC, 1997). Sharing of the copper lines to premises (local loop unbundling or LLU) was initially declared in 2002 (ACCC, 2002), but the regulated prices proved unattractive to competitors, and direct sale and resale of Telstra services remained the dominant mode. The basis for LLU pricing was altered in 2007 (ACCC, 2007a), allowing rival ISPs to connect their own DSL equipment to Telstra's local copper lines for $14.30 instead of $30 per month (ACCC, 2008b). The residential market responded by increasing the market share of Optus and fringe ISPs at Telstra's expense. Between 2007 and 2010 Telstra's number of broadband customers fell by 6% while the total number of Australian fixed broadband subscriptions grew by 70% (Figure 1). The regulator's determinations were often vigorously contested by Telstra, and a plan to upgrade much of the local copper to a higher bandwidth fibre to the node (FTTN) network was halted in 2006 as the ACCC and Telstra failed to reach agreement on competitive access pricing (Burgess, 2006).

Declaring and regulating Telstra's infrastructure increased retail competition and allowed customers meaningful choice within the infrastructure duopoly. However, access to, and the quality of, Telstra-owned exchanges and copper remained problematic for rivals, and there was no apparent path to an upgrade of the fixed telecommunications network (iiNet Pty Ltd, et al., 2007). Furthermore, regulatory requirements discouraged Telstra investment. Telstra instead directed investment to more profitable and less heavily regulated operations associated with mobile telephone and data services (Telstra, 2010). In 2007, the G9 consortium of telecommunication firms (excluding Telstra) proposed building a FTTN network, structurally separated from the investing firms and from Telstra, but also failed to reach agreement with the ACCC on access pricing (ACCC, 2007b).

Network quality became a significant political issue in the 2007 Australian federal election, when the challenging Labor party promised to invest up to 4.7 billion dollars upgrading most of the copper network to FTTN (Farnsworth, 2007). But Telstra, whose cooperation was required to install and connect the new fibre to the existing network, refused to participate without guarantees regarding future regulation (McGauchie, 2008). The government was unwilling to offer such guarantees; Telstra was particularly concerned about forced separation, but was also concerned about future regulatory consistency.

In response, the Australian Government revised its policy in 2009 and established a government-owned company to build a primarily fibre to the premises (FTTP) network, at an estimated cost of 43 billion dollars. The policy initially envisaged the company (NBN Co) being financed with majority government equity plus some private funding, but private investors could not be found and the new company began operations as entirely government-owned. The intention to eventually privatise the company, to recoup the public investment, remained (Wong & Conroy, 2010, p. 12), requiring NBN Co to operate as a long-run profit-making firm.

The new FTTP network would replace Telstra's local copper lines with optic fibre, although it would rent access to Telstra's ducts and other passive physical infrastructure on a wholesale basis. The NBN would only sell wholesale access to retail ISPs, thus achieving structural separation at the local network level. Points of Interconnection (POI) between the NBN and the existing backhaul network were located only where competing backhaul services were already present, to preserve backhaul competition. Telstra agreed to work with NBN Co on access and transition arrangements, and other ISPs broadly welcomed the policy.

Difficulties emerged with the building of the FTTP network, and project delays and concerns about the eventual total cost were issues in the 2013 federal election. A change in government brought a focus on costs and speed of deployment, and in accordance with the recommendations of a cost-benefit study (Australian Government Department of Communications and the Arts Panel of Experts, 2014) the design of the network was modified to include a mix of technologies including FTTP, FTTN and the existing HFC lines. NBN Co accordingly purchased the HFC networks of Telstra and Optus, thus eliminating the fixed infrastructure competition to the FTTN/FTTP network. NBN Co agreed to progressively assume ownership of passive Telstra infrastructure as the NBN replaced Telstra's copper network and DSL broadband services.

Role of Regulation and Industry Concentration

The quantity of broadband units purchased is an important measure of the industry's economic contribution. In the early twenty-first century, many governments supported increased quantity by promoting affordable home broadband. For instance, a key objective of the eEurope initiative was to bring every home "into the digital age and online" (Liikanen, 2000). Many studies of these policies investigate how government and industry actions affected broadband penetration (the typical measure of quantity). A common finding is that broadband adoption is driven by competition between different technological platforms (inter-platform) and not, or less, by competition on a single platform (intra-platform) (Bouckaert, van Dijk, & Verboven, 2010; Cincera, Estache, & Dewulf, 2012; Distaso, Lupi, & Manenti, 2006). Cincera et al. (2012) also found that larger incumbent market shares are associated with slower broadband diffusion. There is some evidence of regulated local loop unbundling (LLU) having slightly positive effects, and other forms of access regulation having small, insignificant or negative effects. Cave (2014), whose work informed much regulatory practice, reviewed results from the period of DSL's technological dominance.

As fixed broadband penetration approached saturation in developed economies (see Figure 2) interest shifted from broadband to "superfast" "next generation" network penetration.

Briglauer (2014) found strong regulation of DSL networks hinders adoption of next generation networks. He has argued that competitive firms invest to escape competition, and so refrain from investing if their competitors will share the rewards. Australia apparently witnessed this effect when neither Telstra nor the G9 consortium were able to agree with regulators on conditions to privately build a FTTN network. Australian regulators must have recognised the benefits of upgrading the network, but were concerned about the effect on consumer prices.

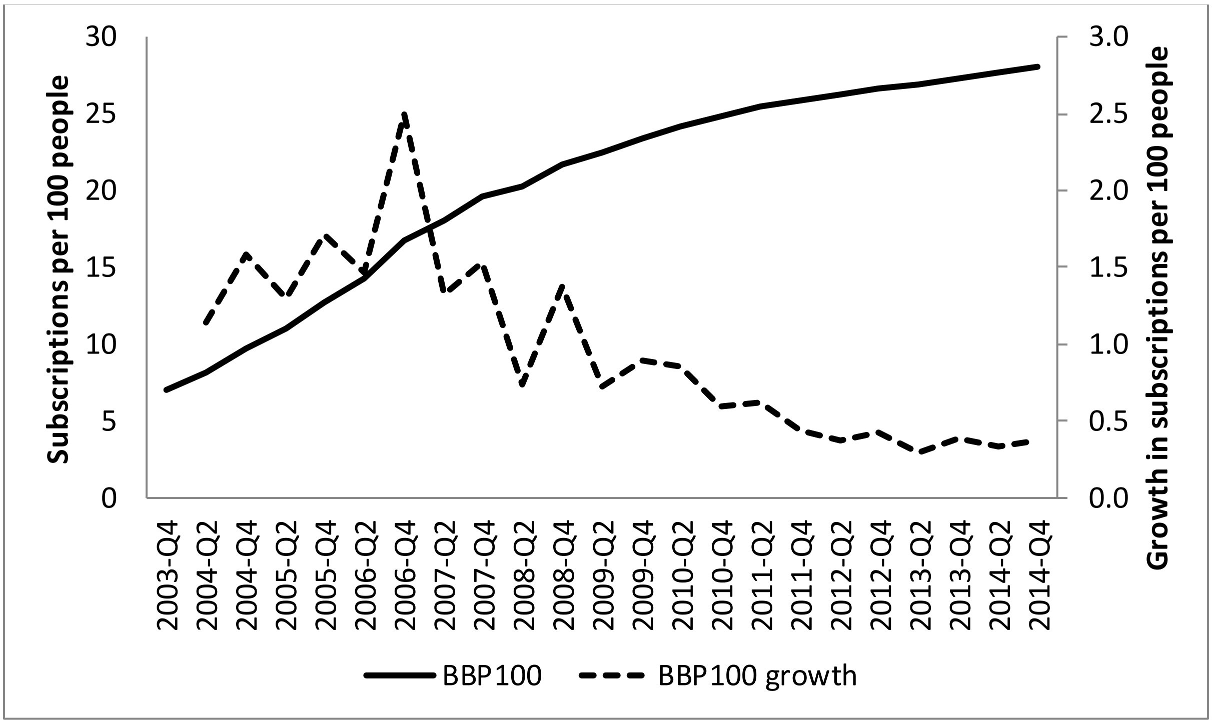

Figure 2. Fixed broadband penetration in OECD nations. (Source: Author's calculation from collated OECD data)

Costs of supply and consumer demand together drive broadband prices. But institutional factors, such as price controls, or market imperfections allowing firms to exploit their market power, may also affect prices. The effect of imperfect competition on price has been detected in particular markets. Correa and Crocioni (2012) used a range of broadband prices in Ireland and the Netherlands to detect which firms in those markets have market power, mitigated by three levels of access regulation. Fageda, Rubio-Campillo, and Termes-Rifé (2014) studied prices in Spain, and found intra-platform competition affects price, while inter-platform competition does not – reversing the common finding for broadband penetration. They also found service-level competition (bitstream access) is significant, results replicated across Europe by Calzada and Martínez-Santos (2014). Studying prices is typically complicated by problems of selecting which broadband price to study from the often large number of offers in the market, and by the need to take account of varying quality.

For the purposes of this article, I consider quality to include all aspects of a product that consumers are willing to pay a higher price for, except quantity. Here quantity is measured as the number of broadband subscriptions, so a contract with a higher download cap, for example, is considered higher quality, not greater quantity. Some aspects of broadband quality are difficult for consumers – and analysts – to assess (Nirmalathas & Lodders, 2016). Service reliability, data transmission speeds, fault resolution and bundled services all influence consumers' product choice, but they are difficult to compare within a market, and even more difficult between markets. Cross-national data on customer satisfaction or complaints regarding home Internet services is not available, so is not considered here. This article accounts for download caps (which are also a direct proxy for advertised download speeds in the data set) in national prices, and for differences in broadband network quality internationally.

Empirical Data and Analysis

In this article I analyse data from the OECD Digital Economy Outlooks (OECD, 2015, 2017) supplemented by a range of other sources covering the OECD economies (Central Intelligence Agency, 2016; OECD, 2013, 2016; Transparency International, 2016; World Bank, 2016). Price data is from a single survey in 2014, so the analysis does not attempt to detect trends over time. It does use some 2016 data, without prices, to check model robustness. The particular value of this data is the inclusion of cross-national broadband prices for comparable bundles ("bundles" here being combinations of advertised speed and data download caps – it excludes "bundles" of Internet services with telephone, pay TV or other services). The data is also relatively recent, coming from generally mature broadband markets serviced by DSL, fibre and HFC technology.

Using the survey's price data does introduce limitations. Broadband consumers typically do not simply select from a range of connection speeds or download caps at single prices. Rather, firms market broadband subscriptions bundled with complementary products, and at differing service levels. Australian firms commonly maintain multiple brands which support price discrimination, as in Telstra's Bigpond and Belong, and TPG's ongoing use of the iiNet and Internode brands from merged firms. Haucap, Heimeshoff, and Lange (2016) address this by testing price diversity as a factor influencing broadband penetration (finding diversity positively affects penetration) but this method is not transferable to the consideration of price as the dependent variable. This article does not attempt to explain price differences within markets, but does consider underlying price differences between markets.

Prices are supplied for 18 standardised bundles per nation, characterised as combinations of advertised speed and data download cap. Not every bundle is available in every nation, and the survey sometimes includes bundles with lower speed or download caps at the same price as bundles offering more. These lower offerings have been excluded from the data, so retained prices represent the most generous bundle offered at that price in that market. The OECD collected advertised price data from the incumbent telecommunications firm, and the largest cable firm, and one alternate firm (all subject to availability), for offers available in the nation's largest city. The survey reports only one price per bundle per nation. In theory, we expect negligible price differences between firms if we assume broadband bundles are interchangeable commodities but, as discussed above, prices in fact show significant variation. In this article, I assume the OECD's data collection method accurately reports incumbent pricing, and that international differences in incumbent pricing (corrected for the incumbents' market share) reflect underlying price differences across markets.

I imputed data to fill occasional gaps in demographic data using methods recommended by Hair (2014), but did not impute missing market share data. Instead, where market share data was unavailable, I excluded the affected nations from parts of the analysis addressing market concentration. Dependent variable distributions from this subset are not substantially different to the whole sample.

I use Ordinary Least Squares (OLS) regression to estimate a control equation for broadband price, initially excluding regulatory and market share information. Regulatory and, separately, market share measures are then added to the specification to see if they make a statistically significant improvement to the control equation's accuracy, i.e. its ability to estimate price. Given sufficient variation of these measures with the sample, finding significant effects would confirm a general capacity for broadband service retailers in more concentrated markets to maintain higher prices through coordinated conduct, and a capacity for access regulation to curtail the effects of coordinated conduct. Coordinated conduct involves firms "implicitly or explicitly coordinating their pricing, output or related commercial decisions" (ACCC, 2008a, p. 30) and may be more sustainable when the number of competitors is fewer. Conversely, the absence of effects would suggest that coordinated conduct is not prevalent, or has effects too small to detect. The analysis is repeated for broadband penetration, which is expected to decrease in situations of oligopoly pricing, and the same factors are checked for any contribution to network quality.

I test market share and concentration using several measures, including those used by regulators (ACCC, 2008a). I calculate the broadly used Herfindal-Hirschman Index (HHI) for retailers' number of subscriptions, independent of connection type, and for connection types, independent of retailers. Other concentration indicators tested included the combined market share of the one, two, three and four largest firms, and Anbarci and Katzman's (2015) industry concentration index, classifying one, two and three firms as dominant. Results using other concentration indices are not substantially different to those using HHI and the incumbents' market share, and are therefore not reported.

More importantly, the only drivers and indicators of market power considered are market share and concentration measures, regulatory settings, and the potential substitutability of wireless broadband for fixed. Barriers to entry other than network access, consumers' countervailing power, the availability of information, and more broadly defined substitutes may all be relevant to market power within particular markets, but due to the difficulty of classifying and comparing these they are beyond the scope of this cross-national analysis.

Principles of parsimony and the modest sample size require including all available useful data while excluding variables which do not add significant explanatory power to the regression equations. I consolidate related factors to single indicators for national population concentration, public investment in telecommunications, national broadband speed, the technological quality of the network, the technological diversity of the network, and the market power of the five largest firms. Table 1 lists the raw factors and Table 2 the consolidated factors tested in the analysis. All factors are naturally numerical, except those representing regulatory options, which I code as dummies indicating presence (1) or absence (0). Three nonexclusive options corresponding to successive rungs on the "ladder of investment" (see OECD (2013) page 10 for a nontechnical description) are included, for low level bitstream access, mid-level unbundled local loop (LLU) access and high level direct (naked) access to the local loop. Mutual interaction terms are also generated for these dummies.

I generate OLS regression equations including all remaining independent variables and factors. I progressively eliminate the least significant variable, and repeat the regression estimation, until the returned Sum of Squares due to Error (SSE) stops decreasing with subsequent eliminations. This stepwise elimination of covariates can produce misleading predictions under some circumstances, so the selection of variables for the control equations was verified using Lasso estimation (Tibshirani, 1996). The confirmation of selected variables by Lasso estimation suggests the retained variables do indeed have consistent effects compared to those eliminated. I note one exception in the discussion of results.

A further robustness check uses the penetration equation generated from 2014 data to estimate penetration in 2016, and compares it to actual penetration. (An updated price survey is unavailable.) The 2014 equation predicts 2016 outcomes quite consistently, with the coefficient of determination (R-squared) only falling from 0.665 in 2014 to 0.577 in 2016.

Table 1 Test variables used in the OLS regressions

Name	Definition
MSn (MS1…MS5)	Cumulative market share of nth largest operator/s, n = 1 to 5
CAP	Fixed Broadband download cap for the associated PRICE bundle
BBP100	Broadband subscriptions per 100 people
NUMDSL	DSL subscriptions per nation
NUMCABLE	Cable subscriptions per nation
NUMFTTX	FTTx subscriptions per nation
NUMOTHERSUB	Other subscriptions per nation
POPTOTAL	Total population per nation (2014)
GDPPC	GDP per capita 2014
POPURBAN	% urban population (OECD classification)
POPINTER	% intermediate urban/rural population (OECD classification)
LANDURBAN	% land urban (OECD classification)
LANDINTER	% land intermediate (OECD classification)
LLU	LLU access regulated, 0=unavailable 1=available
BITS	Bitstream access regulated, 0=unavailable, 1=available
NAKED	Wholesale line access regulated, 0=unavailable, 1=available
PINV	Public investment in telecommunications as a % of telecommunications industry revenue in year #
PINVPC	Public investment in telecommunications per capita, mean for years 2011-2013
WIRELESS	Wireless broadband subscriptions per 100 people, mean for years 2012-2013
AKAMAI	Measure of average actual fixed broadband network speeds (Akamai reported by OECD), high number is fast
OOKLA	Measure of average actual fixed broadband network speeds (Ookla reported by OECD), high number is fast
MLAB	Measure of average actual fixed broadband network speeds (Mlab reported by OECD), high number is fast
EASE	Ease of doing business score 2014, from World Bank, high number is high difficulty
TAX	Top corporate tax rate 2014, from World Bank

Table 2 Composite factors tested in OLS regressions

Factor	Calculation
POPCON	(POPURBAN*LANDURBAN + 0.5*(POPINTER*LANDINTER))/100
PINVC	sqrt(PINV*PINVPC)
SPEED	(AKAMAI/AKAMAI.mean + MLAB/MLAB.mean + OOKLA/OOKLA.mean)*10
TECH	(100*NUMFTTX + 50*NUMCABLE + 20*NUMDSL)/(POPTOTAL*300)
HHIINFRA	MSDSL*MSDSL+MSCABLE*MSCABLE+MSFTTX*MSFTTX+MSOTHER*MSOTHER
HHI5	MS1*MS1+MS2*MS2+MS3*MS3+MS4*MS4+MS5*MS5

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Broadband Outcome Models

Table 3 describes an equation to estimate price. The strongest contribution is wealth, measured as GDP per capita. Household budgets are larger in wealthy economies, so broadband costs and willingness to pay are also higher.

Table 3 OLS regression coefficients for broadband price with regulation and infrastructure concentration variables. Standard errors are in parentheses; n=110.

Factor	Original	With Regulation	With Infrastructure Concentration
Intercept	-17.56 (5.869)	-17.47 (6.881)	-21.01 (6.484)
GDP per capita	0.8430*** (0.111)	0.7932*** (0.0087)	0.7312*** (0.0926)
Corporate tax rate	0.6628*** (0.2079)	0.7651*** (0.2262)	0.6011*** (0.2155)
Download cap	0.0734*** (0.009)	0.07482*** (0.0000)	0.07103*** (0.0086)
Population concentration	-0.3320*** (0.0807)	-0.3538*** (0.0836)	-0.2973*** (0.0791)
Public telco investment	0.1815** (0.0789)	0.2187*** (0.0820)	0.2032** (0.0790)
Wireless penetration	-0.1070* (0.0611)	-0.0781 (0.0639)	
Bitstream access regulation		2.118 (4.4670)	
LLU access regulation		-4.641 (5.4355)	
Naked access regulation		-3.258 (2.9854)	
Infrastructure concentration			3.835 (7.7042)
Adjusted R^2	0.685	0.686	0.676

*** Indicates significance at the 99% confidence level.
** Indicates significance at the 95% confidence level.
* Indicates significance at the 90% confidence level.

The company tax rate also significantly increases consumer prices. Using tax incidence theory, this implies, in accordance with previous research (Galperin & Ruzzier, 2013), that demand for broadband services in OECD countries is relatively price inelastic. Where price demand is inelastic, firms charged high taxes pass the cost on to consumers, knowing that few consumers will drop their subscription in response to a higher price. This implication only extends to the developed economies studied here, and is expected, given the low household-budget share of fixed broadband subscription (less than 2% averaged across the included markets) and the stronger network benefits of Internet access in markets with high penetration.

Higher download caps (which are indistinguishable from higher advertised download speed in the data) generate higher prices, probably both as a reflection of higher costs in backhaul transmission and as effective price discrimination by Internet service providers.

Higher population concentration (the composite factor defined in Table 2) significantly reduces price, likely an effect of network building costs. The effect contributes about 10% to the total price.

Wireless broadband availability has a negative effect on fixed broadband price, although only significant at the 90% level, and less under other model specifications. The low consistency of the effect may reflect a change underway in only some of the economies studied. Technologically improved wireless broadband, previously considered a complement to fixed broadband, is emerging as a substitute in markets such as Finland (OECD, 2017). The possibility of substitution must be considered in Australia, where some measures find wireless network speeds are higher than fixed (speedtest.net, 2017), and is further discussed below.

Public investment raised broadband prices, against expecting public funds to function as a subsidy for customers. Causation is not clear. High prices and public investment could be independent but positively correlated where infrastructure construction is expensive, sharing costs between governments and users. Or public investment could actually support higher prices, by establishing monopolies that crowd out competitive pricing, or if levies on broadband services fund the investment, as considered in Australia (Minister for Communications and the Arts, 2017). The lower significance of this result (from 95% to 99%) suggests variation in the relationship between public investment and prices between markets.

Belying Australia's long political, legal and commercial debates, there is little evidence of competition or market power affecting consumer prices. The interaction of wholesale and local loop access regulation is statistically significant at the 90% level, with a large effect size, but this result is isolated and only tentative without further confirmation. Effects of regulatory settings may be hard to detect because most OECD nations have similar regulatory regimes in place, especially for LLU, and effective regulation across all jurisdictions could be uniformly forestalling monopoly pricing. Or access regulation of ADSL networks may mostly affect the distribution of profits between network owners and access seekers with little flow-through to consumer prices. All OECD broadband markets had five or fewer significant broadband retailers at the time of the price survey, so oligopoly pricing and quantity setting may have persisted generally despite regulation.

Infrastructure diversity did not affect broadband prices.

Table 4 OLS regression coefficients for broadband penetration. Standard errors are in parentheses.

Factor	Original	With Infrastructure Concentration	With Regulation	With Market Concentration
Intercept	14.48 (3.94)	6.56 (4.89)	6.37 (6.22)	6.99 (10.34)
GDP per capita	0.2792** (0.0664)	0.2580*** (0.0621)	0.2559*** (0.0682)	0.2159** (0.0783)
Technology	0.1695*** (0.0567)	0.2163*** (0.0559)	0.2179** (0.0593)	0.2712*** (0.0922)
Ease of doing business	-0.1197* (0.0652)	-0.1330** (0.0607)	-0.1293* (0.0690)	-0.1077 (0.0951)
Infrastructure concentration		13.62** (5.5700)	13.34** (5.9114)	14.40 (8.7414)
Bitstream access regulation			-0.9641 (3.2886)	
Local loop access regulation			0.8540 (4.2976)	
Wholesale access regulation			0.5184 (2.0505)	
Largest firm market share				-0.0029 (0.2963)
Market concentration				-0.0003 (0.0027)
Adjusted R^2	0.674	0.674	0.638	0.525
n	34	34	34	26

*** Indicates significance at the 99% confidence level.
** Indicates significance at the 95% confidence level.
* Indicates significance at the 90% confidence level.

Table 4 summarises the OLS coefficient estimation for quantity, measured as broadband penetration per 100 residents. Per capita GDP is again the driving economic factor – wealthier nations predictably have greater access. Wide use of better technology and consumers concentrating on one form of technology both have positive effects, possibly related, if high technology infrastructure attracts consumers to that technology particularly and to fixed broadband generally. But TECH and HHIINFRA are not strongly correlated (Pearson's correlation coefficient=-0.38) and HHIINFRA does not appear in the Lasso estimate. (Public investment, with a positive sign, is the next coefficient to appear in a Lasso estimate.) The positive influence of better technology is understandable, but the strong positive effect of more homogeneous technology choice is not. As the finding reverses other research discussed above, this anomalous result can be tentatively disregarded. The World Bank's Ease of doing business measure is weakly significant, with the negative sign expected as high numerical scores represent high barriers to business. No regulatory factors are significant in the penetration estimate, and neither are measures of concentration.

I also generate regression equations for speed, as a measure of the quality of broadband service, moderating the price and penetration measures. The speed analysis excludes Korea, as its history of particularly intense infrastructure competition (Brown, 2015) has yielded a

SPEED indicator which is a strong outlier. Results in Table 5 show the technological quality as the only factor to affect speed, with very strong significance. The importance of technology is entirely expected, but the lack of detectable effect from other factors, including public investment and population concentration, is notable. Regulation and competition again show no influence – there is no hint in the data of monopoly networks having lower speed.

Table 5 OLS regression coefficients for SPEED. Standard errors are in parentheses.

Factor	Original	With Regulation	With Market Concentration
Intercept	10.60 (2.94)	8.69 (3.81)	14.44 (7.94)
Technology	0.5609*** (0.0770)	0.5636*** (0.0816)	0.5529*** (0.1020)
Bitstream access regulation		-0.4113 (3.9467)	
Local loop access regulation		4.0425 (4.9541)	
Wholesale access regulation		-2.388 (2.6823)	
Largest firm market share			-0.2612 (0.3703)
Market concentration			0.0026 (0.0034)
Adjusted R^2	0.627	0.554	0.554
n	29	29	23
*** Indicates significance at the 99% confidence level.			

Australia's Position

These empirical models perform well as estimators of national broadband prices, penetration and speed, and all control equations strongly pass the F-test at 99.9% confidence. The equations also predict the associated Australian outcomes well, compared in Table 6. Predicted values are all close to the centres of the 95% confidence intervals. So we can plausibly use these models to explore the determinants of Australian broadband performance.

Table 6 Model estimations for Australia (2014). Low and High estimates are at 95% confidence.

	Actual	Fit	Low	High
Price, 400GB download cap	70	72	46	97
Price, 200GB download cap	51	57	32	83
Price, 100GB download cap	47	50	24	75
Broadband penetration per 100 people	27	31	20	42
SPEED	20	24	12	37

Actual Australian prices (in 2014) are slightly lower than the OECD means for the three download caps considered. According to the model, this is wholly due to the very high number of wireless broadband subscriptions per capita taken up by Australians - almost twice the OECD mean. In every other price factor, Australian factors tend to raise prices above the average. This implies that, within Australia, high take-up of mobile broadband constrains fixed broadband prices. Two related mechanisms may contribute to this. Firstly, as discussed in the preceding section, consumers in some markets may see mobile broadband as a substitute for fixed, so fixed prices must remain comparatively low to retain customers. Australia is a likely market for substitutability to emerge due to the comparatively high quality of its mobile data networks. Australian wireless spectrum policy has historically relied significantly on the functioning of free markets and been less prescriptive than fixed broadband policy. Political disputes, rent seeking or dependency on public spending have consequently not held up wireless technology deployment. Consistent policy has attracted infrastructure investment and competition. Mobile broadband technology deployment in Australia at least matches international peers and sufficient spectrum is available, so mean mobile broadband speeds can even exceed fixed broadband speeds (speedtest.net, 2017).

Secondly, in Australia one incumbent firm is dominant in both fixed and mobile broadband, and, if it is an effective price setter in both markets, it may keep the prices close to avoid cannibalising across its divisions. Figure 3 shows some evidence that Telstra maintains an approximately constant ratio between its fixed broadband and mobile prices. (The notable exception, where average revenue per user moves in opposite directions, is from 2017 and the report does not explain this.)

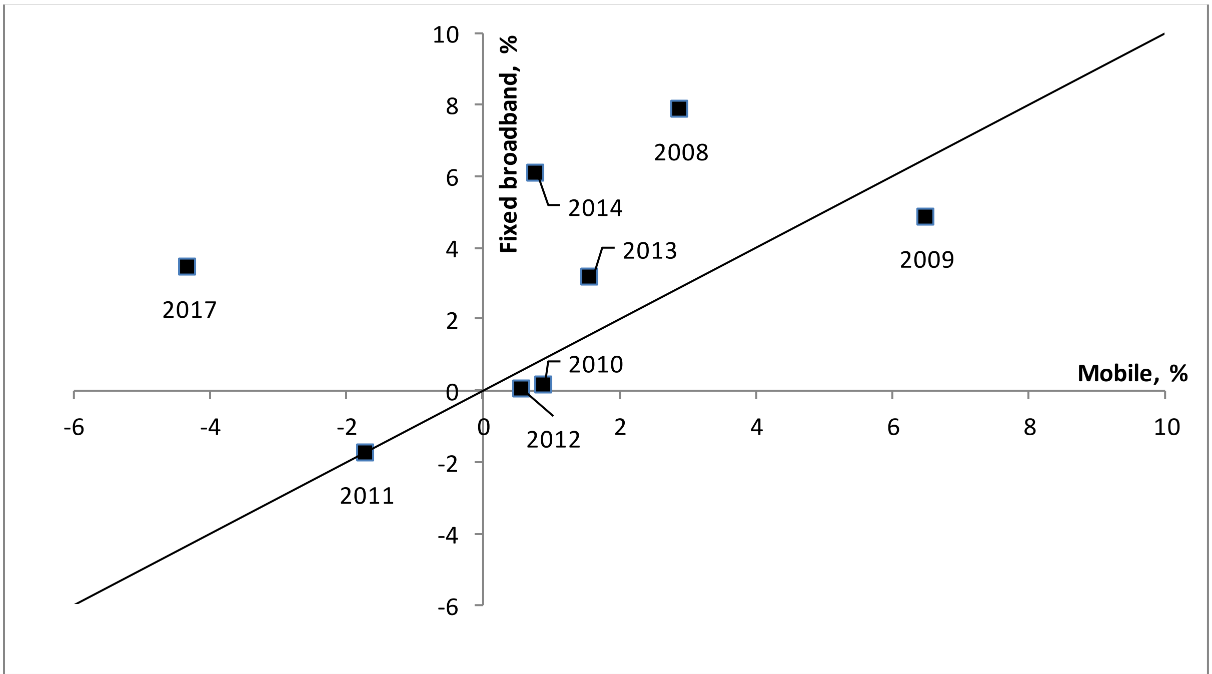

Figure 3. Annual changes in Telstra's average revenue per user (ARPU), 2008-2017. Mobile ARPU is Telstra's blended result 2008-2011, otherwise the unweighted mean of prepaid and postpaid. 2015 and 2016 are omitted due to missing data. The line of equality (not a fitted trendline) is shown for reference. (Source: Telstra Annual Reports 2008-2017)

Australian fixed broadband penetration is very slightly below the OECD average. Australia's low TECH score alone pulls it down; all other factors promoting broadband penetration are above average. The model predicts raising Australia's TECH score merely to the OECD average (i.e. similar to Hungary and Portugal) would increase fixed broadband penetration by 10% (3 additional subscriptions per 100 capita). Early regulatory decisions discouraging commercial investment and the ad hoc establishment of the NBN have both contributed to the technology lag. Fortunately, the problems in fixed broadband are not representative of the whole economy, and Australia's generally business-friendly environment has provided some compensatory support for broadband penetration. With fibre-rich NBN construction well under way, can Australians now expect to enjoy the results of better technology?

Possibly not. Australia's poor absolute network speeds, in these 2014 measurements, are below estimates based only on the then network technology. (In 2014 the NBN served only 3% of Australian subscriptions (NBN, 2014).) This indicates other barriers to quality. Australia's TECH score is 0.71 standard deviations below the OECD mean, while the SPEED score is 0.88 standard deviations below. More recent statistics (speedtest.net, 2017) reveal average network speeds still lag international peers, despite substantial public investment in the NBN. Critics, such as Varghese (2017), argue this is not primarily due to the technology but to the monopoly pricing structure applied to NBN access. The high Connectivity Virtual Circuit charge simulates bandwidth bottlenecks where capacity is not a technical problem. To consumers, the effect is indistinguishable from a technological deficiency, and so we expect that, uncorrected, it will continue to prevent the technological improvements from the NBN from fully contributing to improved broadband penetration and quality measures.

Conclusions

Despite achieving structural separation, results of the twenty-year project to introduce competition into the Australian telecommunications industry are mixed. Retail competition is well established, but with effectively four large firms (ACCC, 2017) it remains below the ACCC's indicative threshold for effective competition, which is equivalent to five equally sized firms (Herfindal-Hirschman Index=2000) (ACCC, 2008a, p. 35). NBN Co.'s purchase of the Telstra and Optus HFC networks, the automatic retirement of DSL following NBN expansion, and legislation mandating the declaration and thence regulation of any new competing networks, mean infrastructure competition is and will remain mostly absent from the local fixed network. If privatisation of NBN Co proceeds, NBN regulation will likely be as complex as regulation of Telstra was. As a profit maximising firm, NBN Co will have incentives to exploit its monopoly by setting high prices and underinvesting in quality, which will have to be constrained.

Australian fixed broadband regulation has been preoccupied with issues – structural separation, retail competition and shared access – that show scant evidence of affecting outcomes. Meanwhile, Australian politics have been concerned with the quantum of public spending without considering whether broad public investment may cost Australians more than they would be willing to pay for the outcomes. The NBN cost-benefit assessment concluded that halting the NBN rollout, or allowing it to proceed unsubsidised, had greater benefits than continuing the rollout at Government expense (Australian Government Department of Communications and the Arts Panel of Experts, 2014 Section 6). But this conclusion was immediately dismissed (Turnbull, 2014).

Due to the limitations of the data discussed above, this article's analytical findings regarding price strictly apply only to incumbent ISPs. I have assumed regulation particularly affects the largest firms, and that pricing decisions by incumbents affect price in the whole market. This concern with the incumbent is also apparent in Australian policy, where Telstra and NBN Co are specifically subject to sections of telecommunications and competition law. I have not considered the possible use of regulation to protect or otherwise benefit an incumbent in other markets, but reviewing regulatory history alongside market outcomes, as has been done here for Australia, could reveal this.

In the international context, the regulatory history of the Australian broadband industry is not exceptional. Most of the policies applied in Australia were also applied elsewhere, with similar results. The outstanding event was the nationalisation of local fixed networks, creating the NBN to resolve the tension between investment and competition, and hence address the outstanding technology deficit. Other jurisdictions have deployed various policies. For example, Canada supplements private investment and access regulation with public subsidy to improve quality only in poorly served areas (Canadian Radio-television and Telecommunications Commission, 2016), similar to Australian Government policy in early 2007 (AFP, 2007). Singapore has established a privately owned, structurally separated fibre to the premises network (Jones, 2015), with a similar role to an eventually privatised NBN. New Zealand has established local (not national) fibre network monopolies, but maintains infrastructure competition with other technologies (Beltrán, 2013).

Establishing the NBN marked a strong shift in Australian regulatory policy, from relying on competing forms to satisfy demand for fixed broadband services, to establishing a protected monopoly to secure investment. The NBN's mixed technology improves the quality of Australian broadband services but, if protecting its monopoly forestalls future technology upgrades (such as extending fibre to the premises where commercially viable), Australian fixed broadband access and quality may continue to lag other developed economies.

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References

ABS. 2017. 8153.0 - Internet Activity, Australia, December 2017, Glossary. http://www.abs.gov.au/AUSSTATS/abs@.nsf/Latestproducts/8153.0Glossary1December%2017

ACCC. 1997. ACCC issues its statement of deemed declared services for telecommunications access [Press release]. https://www.accc.gov.au/media-release/accc-issues-its-statement-of-deemed-declared-services-for-telecommunications-access

ACCC. 2002. ACCC declares line sharing [Press release]. https://www.accc.gov.au/media-release/accc-declares-line-sharing

ACCC. 2007a. *Unconditioned Local Loop Service (ULLS) Final Pricing Principles*. https://www.accc.gov.au/regulated-infrastructure/communications/fixed-line-services/unconditioned-local-loop-service-pricing-principles-2007/ulls-pricing-principles-2007.

ACCC. 2007b. *Assessment of FANOC's Special Access Undertaking in relation to the Broadband Access Service Draft Decision*. https://www.accc.gov.au/system/files/ACCC%20draft%20decision%20on%20FANOC%20SAU%20-%20Dec%2007.pdf

ACCC. 2008a. *Merger Guidelines, amended November 2017*. Commonwealth of Australia https://www.accc.gov.au/system/files/Merger%20guidelines%20-%20Final.PDF.

ACCC. 2008b. Telecommunications draft principles & prices, access terms issued [Press release]. https://www.accc.gov.au/media-release/telecommunications-draft-principles-prices-access-terms-issued

ACCC. 2017. *NBN Wholesale Market Indicators Report 30 September 2017*. https://www.accc.gov.au/regulated-infrastructure/communications/national-broadband-network-nbn/nbn-wholesale-market-indicators-report/reports

ACMA. 2017. *Australian Communications and Media Authority communications report 2016-17*. www.acma.gov.au/commsreport

AFP. 2007. 'Australia announces vast national broadband plan', *The Sydney Morning Herald*, 18 June 2007. http://www.smh.com.au/news/Technology/Australia-announces-vast-national-broadband-plan/2007/06/18/1182018999327.html

Anbarci, N; Katzman, B. 2015. 'A New Industry Concentration Index', *Economic Papers: A journal of applied economics and policy*, 34(4), 222-228. http://dx.doi.org/10.1111/1759-3441.12122

Australian Government Department of Communications and the Arts Panel of Experts. 2014. *Independent cost-benefit analysis of broadband and review of regulation*. https://www.communications.gov.au/sites/g/files/net301/f/Cost-Benefit_Analysis_-_FINAL_-_For_Publication.pdf

Baldwin, R; Cave, M; Lodge, M. 2011. *Understanding Regulation: Theory, Strategy, and Practice*. Oxford: Oxford University Press.

Beltrán, F. 2013. 'Fibre-to-the-home, high-speed and national broadband plans: Tales from Down Under', *Telecommunications Policy*, 38(8-9), 715-729. https://doi.org/10.1016/j.telpol.2013.08.006

Bouckaert, J; van Dijk, T; Verboven, F. 2010. 'Access regulation, competition, and broadband penetration: An international study', *Telecommunications Policy*, 34(11), 661-671. http://dx.doi.org/10.1016/j.telpol.2010.09.001

Briglauer, W. 2014. 'The impact of regulation and competition on the adoption of fiber-based broadband services: recent evidence from the European union member states', *Journal of Regulatory Economics*, 46(1), 51-79. http://dx.doi.org/10.1007/s11149-013-9237-4

Brown, N A. 1990. *Telecommunications Reform Bill*. http://kirra.austlii.edu.au/au/legis/cth/bill/trb1990293/

Brown, T. 2015. 'South Korea: What happened to the broadband wonderland?', NBN online, 5 February 2015. https://www.nbnco.com.au/blog/industry/south-korea-what-happened-to-the-broadband-wonderland.html

Burgess, P. 2006. Transcript from Telstra Fibre to the Node Briefing - Teleconference [Press release]. http://www.asx.com.au/asxpdf/20060807/pdf/3xwj5q0vmnlsm.pdf

Calzada, J; Martínez-Santos, F. 2014. 'Broadband prices in the European Union: Competition and commercial strategies', *Information Economics and Policy*, 27, 24-38. http://dx.doi.org/10.1016/j.infoecopol.2014.04.001

Canadian Radio-television and Telecommunications Commission. 2016. CRTC establishes fund to attain new high-speed Internet targets [Press release]. https://www.canada.ca/en/

radio-television-telecommunications/news/2016/12/crtc-establishes-fund-attain-new-high-speed-Internet-targets.html

Cave, M. 2014. 'The ladder of investment in Europe, in retrospect and prospect', *Telecommunications Policy,* 38(8-9), 674-683. http://dx.doi.org/10.1016/j.telpol.2014.04.012

Central Intelligence Agency. 2016. *The World Factbook*. https://www.cia.gov/library/publications/the-world-factbook/

Cincera, M ; Estache, A; Dewulf, L. 2012. 'On the (In) Effectiveness of Policies to Promote Broadband Diffusion in Europe (2003-2010): An Econometric Assessment', *IDEAS Working Paper Series from RePEc*. https://ideas.repec.org/p/eca/wpaper/2013-128909.html

Correa, L; Crocioni, P. 2012. 'Can evidence of pricing power help market power assessment? Broadband Internet in Ireland and the Netherlands', *Telecommunications Policy,* 36(5), 419-433. http://dx.doi.org/10.1016/j.telpol.2011.11.014

Distaso, W ; Lupi, P ; Manenti, F M. 2006. 'Platform competition and broadband uptake: Theory and empirical evidence from the European union', *Information Economics and Policy,* 18(1), 87-106. http://dx.doi.org/10.1016/j.infoecopol.2005.07.002

Farnsworth, M. 2007. 'Rudd Launches Broadband Policy; Abandons Opposition to Telstra Sale', *Australianpolitics.com*. http://australianpolitics.com/2007/03/21/rudd-launches-broadband-policy.html

Fageda, X ; Rubio-Campillo, R; Termes-Rifé, M. 2014. 'Determinants of broadband access: Is platform competition always the key variable to success?' *Information Economics and Policy,* 26, 58-67. http://dx.doi.org/10.1016/j.infoecopol.2013.12.001

Galperin, H; Ruzzier, C A. 2013. 'Price elasticity of demand for broadband: Evidence from Latin America and the Caribbean', *Telecommunications Policy,* 37(6), 429-438. doi:https://doi.org/10.1016/j.telpol.2012.06.007

Hair, J F *et al.* 2014. *Multivariate Data Analysis* (Seventh edition, Pearson New International Edition. ed.): Harlow Pearson Education Limited.

Haucap, J; Heimeshoff, U; Lange, M R J. 2016. 'The impact of tariff diversity on broadband penetration—An empirical analysis', *Telecommunications Policy,* 40(8), 743-754. http://dx.doi.org/10.1016/j.telpol.2015.09.005

iiNet Pty Ltd; Agile Pty Ltd; Amcom Pty Ltd; Adam Internet Pty Ltd. 2007. *Fixed Services Review - Further consultation on draft ULLS pricing principles*.

https://www.accc.gov.au/system/files/iiNet%2C%20Amcom%2C%20Agile%20and%20Adam.pdf

Jones, D S. 2015. 'Infrastructure management in Singapore: privatization and government control', *Asian Education and Development Studies,* 4(3), 299-311. http://dx.doi.org/10.1108/AEDS-12-2014-0064

Liikanen, E. 2000. 'eEurope: An Information Society For All' (Erkki Liikanen, Member of the Commission Enterprise and Information Society)(Transcript). *Presidents & Prime Ministers,* 9(2), 18. http://europa.eu/rapid/press-release_SPEECH-01-180_en.htm?locale=en

McGauchie, D. 2008. 'National Broadband Network - Telstra Proposal', Electronic Lodgement, 26 November 2008. http://www.asx.com.au/asxpdf/20081126/pdf/31dtyjbyvcgnvj.pdf

Minister for Communications and the Arts. 2017. *Telecommunications (Regional Broadband Scheme) Charge Bill 2017*. Canberra: House of Representatives https://www.aph.gov.au/Parliamentary_Business/Bills_LEGislation/Bills_Search_Results/Result?bId=r5916.

NBN. 2014. *nbn annual report 2014*. https://www.nbnco.com.au/content/dam/nbnco2/documents/nbnco-annual-report-2014.pdf

Nirmalathas, T A; Lodders, A. 2016. 'How to choose the best NBN plan for your needs', *The Conversation*, 16 December 2016. http://theconversation.com/how-to-choose-the-best-nbn-plan-for-your-needs-68424

OECD. 2013. 'Broadband Networks and Open Access'. In *OECD Digital Economy Papers*. Paris: OECD Publishing. http://dx.doi.org/10.1787/5k49qgz7crmr-en

OECD. 2015. *OECD Digital Economy Outlook 2015*. http://dx.doi.org/10.1787/9789264232440-en

OECD. 2016. OECD Broadband Portal. http://www.oecd.org/sti/broadband/oecdbroadbandportal.htm

OECD. 2017. *OECD Digital Economy Outlook 2017*. http://dx.doi.org/10.1787/9789264276284-en

Richardson, D. 1997. 'Telstra: Privatisation Issues', *Current Issues,* 8. https://www.aph.gov.au/sitecore/content/Home/About_Parliament/Parliamentary_Departments/Parliamentary_Library/Publications_Archive/CIB/CIB9697/97cib8

Sims, R. 2017. 'Ceteris paribus, competition is king'. Paper presented at the 2017 Annual Conference of Economists, Sydney, Australia. https://www.accc.gov.au/speech/ceteris-paribus-competition-is-king

speedtest.net. 2017. 'Speedtest Reports; Australia; Fixed', *Speedtest Reports*, 8 November 2017. http://www.speedtest.net/reports/australia/#fixed

Telecommunications Act 1991 (Cth)(Austl.). https://www.legislation.gov.au/Details/C2004C07512

Telecommunications Act 1997 (Cth)(Austl.). https://www.legislation.gov.au/Details/C2017C00357

Telstra (Dilution of Public Ownership) Act 1996 (Cth)(Austl.). https://www.legislation.gov.au/Details/C2004A05097

Telstra. 2010. *Telstra Annual Report 2010 - Directors' Report*. https://www.telstra.com.au/aboutus/investors/financial-information/reports

Tibshirani, R. 1996. 'Regression Shrinkage and Selection via the Lasso', *Journal of the Royal Statistical Society. Series B (Methodological),* 58(1), 267-288. http://www.jstor.org/stable/2346178

Transparency International. 2016. *Transparency International - The Global Coalition Against Corruption*. https://www.transparency.org/

Turnbull, M. 2014. Vertigan panel lays out path to less telecommunications regulation [Press release]. http://www.minister.communications.gov.au/malcolm_turnbull/news/vertigan_panel_lays_out_path_to_less_telecommunications_regulation

Varghese, S. 2017. 'NBN woes: govt must carry the can, says Paul Budde', ITWire, 8 August 2017. https://www.itwire.com/telecoms-and-nbn/79345-nbn-woes-govt-must-carry-the-can,-says-paul-budde.html

Wong, P; Conroy, S. 2010. *Statement of Expectations for the NBN*. Letter to NBN Co [undated]. http://www.nbnco.com.au/content/dam/nbnco/documents/statement-of-expectations.pdf

World Bank. 2016. World Bank Open Data. http://data.worldbank.org/