AJTDE Volume 5, Number 1, March 2017

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Telecommunications Performance Monitoring and Unlimited Data

Editorial

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Abstract: The Australian telecommunications industry has been slow to call for or to adopt new practices and the National Broadband Network has exacerbated the problem of technology adoption lag. There are two key issues facing telecommunication consumers today. The cost of optical networking has significantly reduced over the past five years so there is no justification for the network congestion that occurs on Australian telecommunication networks. To remedy this situation the introduction of performance monitoring is fully supported. It is time for the telecommunications industry to adopt new broadband business models that are based on the provision of unlimited data and a maximum of 90 to 95 per cent utilisation on optical network links.

In This Issue

In this issue the *Journal* includes topical articles that cover Australian telecommunications, historical events and an article of the state of telecommunications in Mexico.

Avatars in the Trumpocene takes a satirical look at the potential outcomes of the Trump Presidency. For media, the French Presidential system of government, adopted by the U.S., provides an endless stream of stories, many of which are quite bewildering. It is with this backdrop that *Edouard Estaunié* considers what might happen next.

30 Years after Launch provides a brief history of Telecom Australia's launch of a mobile cellular service in Australia. This strategic decision has led to an explosion of mobile cellular that provides Australian's with unprecedented mobility and coverage.

The Seymour-Bendigo Pole Route is a fascinating look at the construction, in 1952, of an aerial trunk route and the challenges faced.

http://doi.org/10.18080/ajtde.v5n1.95

A Trust-Aware RPL Routing Protocol to Detect Blackhole and Selective Forwarding Attacks addresses blackhole and selective forwarding attacks and provides a trust-based routing protocol for low-power and lossy networks.

Review of the Mexican Telecommunications Market discusses the shift from an incumbent government owned monopoly to a competitive telecommunications market in Mexico and highlights the favourable outcomes achieved.

A New QoS Routing Northbound Interface for SDN introduces a software-defined constrained optimal routing algorithm for improved QoS routing and traffic engineering.

The Tragedy of Australia's National Broadband Network reviews recent developments in global broadband deployments, highlights the growing global dominance of fibre to the premises and argues that the increasing deployment of fibre to the node is not beneficial to Australia's future.

Telecommunications Performance Monitoring and Unlimited Data

The recent announcement by the Australian Government that it would fund broadband performance monitoring is a giant leap forward for consumers that have been caught in a vortex caused by the Australian telecommunications industry failing to remove data usage restrictions. The Australian telecommunications industry has maintained a structure and business approach based on data utilisation charges, partly due to the high cost data transmission, both nationally and internationally.

Over the past five years, the cost of optical networking has reduced significantly and when coupled with the growth of content delivery networks that push content closer to consumers, there is no justification for the previous business model to be retained.

Broadband performance monitoring will highlight what we already know, and that is the daily congestion experienced by consumers is alarming high and unacceptable moving forward.

A shift to unlimited data for a fixed wholesale access monthly charge at each broadband connection speed tier should be adopted immediately. The telecommunications industry should agree upon a set maximum of 90 to 95 per cent utilisation on wholesale or regulated optical networks.

If the industry fails to act, Government should regulate the shift to unlimited data and the provision of sufficient capacity over wholesale or regulated optical networks to ensure that congestion cannot occur.

The telecommunications industry needs to work with content providers to ensure that consumer experience improves dramatically from the unacceptable situation today.

Further data compression is not the panacea and it is vital that the quality of content provided over broadband networks improves dramatically. For content providers to improve the quality of their offering the Government and the telecommunications industry needs to take the first step.

Looking Forward

The key themes for 2017 will be *International Telecommunications Legislation and Regulations* and *International Mobile Cellular Regulation and Competition*. As the global digital economy evolves it is timely to consider the different telecommunications markets and how each is coping with the transition to next generation networks – the 'gigabit race' – and how competition is being fostered with the market. Mobile cellular continues to be an expensive consumer product and for many nations the promise of a competitive mobile cellular market has not eventuated due to the inherent advantages enjoyed by incumbent telecommunication companies during the deregulation years.

Papers are invited for upcoming issues and with your contributions the Journal will continue to provide the readership with exciting and informative papers covering a range of local and international topics. The Editorial Board 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 a peer-review process.

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http://doi.org/10.18080/ajtde.v5n1.95

Avatars in the Trumpocene

Edouard Estaunié
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Abstract: This Journal's intrepid reporter Edouard Estaunié provides a first-hand account of new developments presented at Telecoms 2030, the first global telecommunications conference to be held after the devastating Trump Wars.

Keywords: Telecommunications, Donald Trump, avatars, 2030, satire

Excitement is high this morning as we fly into Sydney for Telecoms 2030, the first re-emergence of this global industry conference since the disastrous Trump Wars.

Enrolment from Americans, Chinese and Russians is expected to be low, as all their major cities were nuked in the Mutually Assured Destruction unleashed once Donald hit the red button. The radiation levels in the debris of the target cities remain off the scale. A major application of the Internet of Things now lies in monitoring radiation counters – and air pollution counters – around the globe, and in providing hazard alerts.

The world's political boundaries have drastically changed. We know that China's mainland population, reduced to a paltry hundred million since the terrible conflagation, still exceeds America's residual eighty million survivors, many eking out primitive existences away from their doomed cities. The Russian Oligarchs have reclaimed Alaska and the Baltic States. The Chinese warlords, safe in their mountain bunkers, have claimed the north of Australia, after nuking the US bases at Darwin and Pine Gap. They'd already owned 80% of the farmland anyway.

The new southern Chinese frontier – known to us ironically as the Hanson Line – extends from Cable Beach to Tweed Heads. One upside is that they are showing more care in protecting the Great Barrier Reef – or at least its southern, relatively unbleached rump - than our pre-War Bernardi government ever did. The Reef is now an armed extension of the radically extended South China Sea.

Helga, my colleague from EU Telekom, is saddened. Looking at the images of harbour captured by the plane's external infrared cameras, she has seen how much Sydney has changed since her pre-War visits. It's not just the dense, purplish grey air pollution covering the city. Sydney, after all, was spared from nuclear annihilation, once Australia had signalled to China its neutrality, in first the Trump Trade War and then his Apocalypse Now. But the

http://doi.org/10.18080/ajtde.v5n1.86

air pollution blowing across the globe is unavoidable, and southern Australia is spared the worst.

No, what has saddened her are the effects of the rising sea: all the harbour beaches are now well under water, and the beauty of the Sydney Opera House is obscured by the four-metre high dykes built to protect it. For the present, the Sydney Harbour Bridge remains high enough to be still usable by road and train traffic.

Our plane is landing itself at Sydney's Badgerys Creek Airport. The former international airport on the east coast is well below sea level, and its protective dykes only permit the landing of much smaller craft. All the contentious pre-War debates about using pilotless planes have been made irrelevant by the horrific changes to the atmosphere, in both turbulence and contamination. Fully automated navigation and aircraft control systems are now quite essential. We land very smoothly, and taxi to the reception portals.

After passing the iris-controlled immigration doors, Helga and I join dozens of other delegates in a commodious driver-less bus arranged by the conference organizers.

Why are there so many attendees this year? Some had predicted that the perfection of avatars and the deployment of giga-speed communications links would negate any further need for conferences. And indeed several of the keynote speakers tonight will be the avatars of home-bound celebrity CEOs. But the gregariousness impulse amongst humans has remained important. The avatar keynote sessions at this conference will be far less popular than those with a real speaker in the room.

With our luggage automatically transported from the airport to our hotel rooms via separate buses, we can go straight to the conference reception area. Once again, iris recognition technology is used to register us conference attendees. I am pleased to see a handful of old friends from the US who have survived the Trump Wars against the odds, and now belong to major research centres in unscorched centres in Canada, New Zealand, the recombined Korea and the new Federation of Free Europe.

One of them is Tony Kerrikov, a stalwart of Amazon Bell Labs who had the luck to be abroad in independent, neutral Scotland when his laboratories back in New Jersey were obliterated. He hails me from across the foyer. "Hey, Edouard! Great to see you! Are you coming to my session?"

Tony's forte was deep packet inspection, before the Wars. He's since teamed up with nanobiologists at Glasgow Tech to create a new field called Molecular ID. Now just the smear of sweat from a finger, not a fingerprint, can be used to identify an intruder, within certain probabilities. It's a potential boon to forensic scientists as well as, controversially, to security services worldwide. And of course to the telcos transmitting the digitally encoded, complex molecular signatures via the Internet of Things.

However the biggest panel session at Telecoms 2030, to be chaired by Helga, is focussed on avatars. The use of avatars is now vital to commercial telecoms: they are the biggest factor in the growth of ultra-broadband traffic. Their 3-dimensional verisimilitude greatly outperforms the ghostly shapes of the pre-war holographs; they have all the appearance of solid lifeforms, until physically 'touched' by the curious or unwary. Their latency in mimicking or carrying out the instructions of their owners has been reduced to milliseconds, when using giga-link connections. Avatars of course make ideal substitutes for their owners when avoiding expensive travel, or, more typically in this sorry trumpocene, in visiting dangerous locations.

At the end of this session, the chairperson, Helga, dramatically reveals herself to be an avatar. Her real self is in the control booth at the back of the auditorium. (Clever *Fräulein,* that Helga.) She then asks: press the green button on your desk if you are a real life-form, and the orange button if you are an avatar. The audience laughs: of course the avatars haven't yet got the ability to apply pressure to buttons, have they? "That's OK," says Helga, "We know we have 200 desks in this room, and most are occupied. Let's see how many green buttons are pressed."

On the room's main screen above Helga, a computer facsimile of the auditorium starts lighting up with green lights. After a few seconds' pause she asks, has everyone had time to press their button?

Only 35 green buttons have lit up out of the potential 200. But alongside them, 162 orange buttons have been activated.

"That's a convincing majority for the avatars", says Helga. "Which helps us with our next decision. Our Program Committee has nominated the Trump Hotel in Washington DC as the venue for Telecoms 2031. Because radiation levels around the hotel are so high, we've been offered free registration for our conference. Please indicate if you plan to attend Telecoms 2031."

162 orange buttons light up.

30 Years After Launch

Recalling the First Four years of Telecom's Cellular Mobile Service

Ian Campbell

Telecommunications Association

Abstract: This year is the 30th anniversary of Telecom Australia's launch of the cellular mobile service in Australia. There has been a huge evolution in mobile services since then.

The Postmaster-General's Department (PMG) introduced a manually (operator) connected mobile service in Australia in 1950. As this service approached full capacity, Telecom launched a Public Automatic Mobile Telephone Service (PAMTS) in 1981. The PAMTS service had no future technology evolution, a 12 year life, and reached a peak of 14,000 customers.

By 1985 a small engineering team had developed a cellular mobile service concept based on the Analogue Mobile Phone Service (AMPS) standard. Development was accelerated and refined and the service was launched in 1987, arguably two and perhaps three years late.

This is the story of the development and launch of the service and the growth over the first four years to 1991.

Noting the experience of cellular operators in the USA, Canada and the UK, Telecom's mobile service concept was a "gold standard" for cellular services around the world, and the service achieved one of the fastest growth rates in its early years.

Within four years it was a cash flow powerhouse, and one of only three services within Telecom that were profitable; the others were the basic telephone service and directory publishing.

When transferred to Telstra in 1992 it was a strategically strong, highly profitable business prepared to defend against competition being introduced into the Australian telecommunications market, and was a foundation of Telstra's financial strength for the next 30 years.

Introduction

In 1974 the Vernon Royal Commission of Inquiry into the Post-Master General’s Department (PMG) recommended to the Whitlam Labor Government that the PMG be split into two businesses, the Australian Telecommunications Commission (Telecom Australia) and the Australian Postal Commission (Australia Post). Each business was to be operated using "commercial business principles", with personnel and other employment policies, including industrial relations, suited to the new business and independent of the Public Service Board.

http://doi.org/10.18080/ajtde.v5n1.87

The new Telecom was designed and implemented in 1975 by senior managers transferring from the PMG. Key recommendations of the Vernon Report were not implemented; for example, the new district organisation was based on state boundaries rather than on commercial criteria; the one senior manager appointed from the private sector had little commercial experience; and the personnel and other employment policies, processes, and culture of the public service were retained. From 1975 until 1989, except for a brief period, there was only one senior manager in Telecom who had significant commercial, private sector experience.

The resulting business was minimally commercial in organisation, skills, focus, priorities and processes. Telecom, with its monopolies, union constraints and public sector legacy, preferred change on its own terms with minimal risk; it was familiar with managed technical change but not commercial change.

This background is crucial to understanding Telecom's approach to the introduction of mobile services in Australia.

The Australian Telecommunications Act 1975 required Telecom to "best meet the social, industrial and commercial needs of the Australian people for telecommunications services" and "make those services available throughout Australia for all people who reasonably required those services", including "the special needs for telecommunications of those who resided or carried on business outside the cities". The Act introduced the concept of a "Universal Service" – the provision of a baseline telephone service to every resident and business in the nation at a minimum quality of service at affordable nationwide rates. This meant that rates charged for the telephone service would be the same for customers in urban, rural and outback areas, even though the telephone service outside the cities and major towns operated at a loss.

To finance the cross-subsidy the regulated monopolies enjoyed by the PMG were continued for Telecom: building and operating the national telecommunications network (including mobile networks) and the sale, rental and maintenance of certain customer premises equipment, providing a market share approaching 90%. More transparent forms of funding the cross-subsidy were overlooked, the main aim appearing to be to reassure Telecom's management, staff and unions so that there was a smooth transition from the PMG to Telecom.

The new Telecom was a massive business. It was the largest capital enterprise in the country with assets almost double those of Australia's biggest private company, BHP. In the first year revenue was $1.4 billion, profit was $152 million and there were over 87,000 employees.

Disclosure

This is not an academic paper; a more apt description would be a reflective recollection of the early years of the cellular mobile service in Australia.

The paper is supported by a number of records from the period, including business plans, business cases and trading statements, as listed under "References". The records are incomplete but are sufficient to support the points made. A number of these records no longer exist or are not easily accessible, such as those in the archives of the Australian Telecommunications Commission and Telstra.

Opinions and judgments about Telecom are expressed using standard private sector criteria including growth, market share, customer service and profit, rather than using public service criteria.

The paper provides some detail about Telecom's task as the national carrier and its operations and culture to afford a better understanding of judgements and events. Other mobile services are mentioned as a context for the cellular mobile service.

Telecom in 1981

1981 seems to have been a pivotal year for Telecom; pressure was building for relaxation of Telecom's monopolies and Telecom launched a new mobile service.

During the first six years Telecom's business was booming; the annual growth rate from 1975 ranged from 8 to 13%, and 14% in the last year to $2.6 billion. Telephone services had increased from 3.7 million to 5.1 million. Almost 80% of homes in Australia now had phones, up from 62% in 1975.

In 1975 the public network primarily carried voice traffic, but by 1981 a major data market and a value-added services market began to emerge.

Even with its monopoly advantages, Telecom faced a number of huge challenges in the early years. For example, a new national district organisation with some 83 districts was implemented throughout Australia in the first three years. A new computer-based District Customer Record Information System (DCRIS) for processing telephone service transactions was being deployed in the districts, converting over three million paper-based telephone customer service records to the new system by 1985. Emerging technologies, particularly digitisation, optic fibre and computer controlled exchanges, offered a wider range of services and significantly lower capital and operating costs. Government and business networks were growing in size and complexity.

It was clear that Telecom's introduction of new products and services and modernisation of the network were falling behind, particularly in mobile and data services.

Aggressive and massively damaging industrial action taken by the Australian Telecommunications Employees Association (ATEA) in 1978 angered many in government, commerce and industry, and action threatened again in 1981.

By 1981 there was mounting pressure for competition in Australia's telecommunications market. Large businesses were demanding relaxation of Telecom's monopolies, full access to the customer premises equipment market and the right to provide network services.

In short, in the six years since Telecom was formed, not only had the market changed radically, but technology and other factors, including industrial action, seemed to make the relaxation of Telecom's network and permitted attachments monopolies almost inevitable.

The Davidson Inquiry

In response to the calls for telecommunications de-regulation, in 1981 the Fraser Coalition Government commissioned an inquiry into "Telecommunications Services in Australia" – the Davidson Inquiry – to determine the desired level of involvement of the private sector in the delivery of existing and proposed telecommunications services, including "value added" services.

In 1982 Davidson recommended far-reaching reforms in Australia's telecommunications market. Five of the most important were: permitting independent networks with no restriction on use; networks based on Telecom's leased lines; resale of capacity leased from Telecom; the interconnection of private networks with Telecom's network; and introducing full competition for marketing and maintenance in the terminals and the value-added services markets. An independent regulator would approve attachments to the network.

It is interesting that Davidson appears to have considered landline and mobile networks together, although satellite networks are mentioned separately.

The Davidson Report raised some of Telecom's worst fears. Telecom had minimal commercial capability and no sales capability. Competition, depending on the form and timetable, foreshadowed a rapid decline in market share. Deregulation of the telecommunications market in the USA indicated that Telecom could conceivably lose over 30% of its market share within a decade.

In March, 1983, the incoming Hawke Labor government shelved almost all of Davidson's recommendations except for some relaxation of the regulation of customer premises equipment.

This at least provided some time for Telecom to become more competitive.

Telecom's Entry to Australia's Mobile Services Market

In 1950 the PMG launched a manually (operator) connected mobile telephone service using base stations serving a large area. This system had a very limited capacity, allowing only hundreds of services in a city, and there was a long waiting list for connection. The car- or truck-mounted mobile telephones were made locally by Amalgamated Wireless Australia (AWA), were very large and heavy, and coverage was limited. Towards the late 1970s demand was expected to exceed the capacity of the service.

At the same time first-generation cellular mobile technology (1G) emerged, which made mobile communications practical for mass markets; the first commercial service was launched by Nippon Telephone and Telegraph (NTT) in Tokyo in 1979. Pressure was mounting on Telecom, with its monopoly for public services, to provide a superior automatic telephone service which would support the growing mobile market.

1G cellular systems such as the USA's Advanced Mobile Telephone System (AMPS) and the Nordic Mobile Telephone System (NMT) were proposed within Telecom but were not commercially available. AMPS was first launched in Chicago, Illinois, in 1979, and NMT in Finland, Sweden, Demark and Norway in 1981.

After calling for tenders in 1978, Telecom selected a system supplied by the Nippon Electric Company (NEC) for which the network and mobile equipment was locally assembled. Named PAMTS – Public Automatic Mobile Telephone System – the system and mobiles were based on a system supplied by NEC to Nippon Telephone & Telegraph (NTT) and other markets such as Hong Kong. The design of the PAMTS system was not cellular in that channel frequencies were not reused in an area, although a call could be handed over slowly from one base station to another as the mobile moved around the coverage area.

The PAMTS system was launched in August, 1981, in Melbourne with just three base stations, and was rolled out to Sydney, Brisbane, Perth, Adelaide and the Gold Coast. The number of customers reached a peak of 14,000 before gradually declining following the launch of the "true" cellular service, and was finally closed in 1993.

PAMTS mobile units were usually mounted in cars and, weighing 9 kg, were only nominally mobile. The mobile units cost $4,999 (equivalent to around $18,000 in 2016) to buy and $1,000 per year ($3,500/2016) to rent. The initial connection fee was $350 ($1,200/2016), a typical installation cost $150 ($500/2016), and the annual network access cost was $800 ($3,000/2016). All calls were at Subscriber Trunk Dialling (STD) timed rates with a minimum cost, including for local calls, of 39 cents per minute ($1.40/2016). With the monopoly, Telecom was the only provider for the service and the only installer in cars and trucks.

The PAMTS system had several serious shortcomings. The technology was obsolete when launched and had no future evolution. The number of customers it could serve was limited and, after 1983, was far less than the scale of market demand emerging for 1G services elsewhere. PAMTS customers were not offered the rapid fall in mobile terminal prices with the escalating volumes experienced in 1G markets after 1984.

The delay until 1987 for the launch of a 1G service in Australia was costly to Telecom and the nation. The number of cellular mobile services in operation in 1990 was 200,000 and in 1993 915,000. If the service had been launched in 1984 or 1985 , two or three years earlier, the benefit to the economy and the customers would have been very substantial, perhaps exceeding $400 million in revenue to Telecom and several times more in economic activity in Australia.

Telecom's Cellular Mobile Service

By 1982 the progress in places such as the USA, the Nordic countries, Japan and Hong Kong clearly demonstrated the scale of demand and profitability of cellular mobile services.

By 1985 the Australian market was well aware of the popularity of the cellular service overseas and there was mounting pressure for a similar service in Australia, particularly from the business sector. The potential profits from cellular services in Australia were too high for the private sector to be excluded for long. By 1985 a small engineering team in Telecom had developed a limited cellular mobile concept based on the AMPS standard. In the following two years this was accelerated and refined and the service was launched in 1987, arguably two and possibly three years late.

The (Cellular) "Mobilenet" Service Concept

Telecom's Commercial Services people had extensively researched two broad models for cellular network services overseas; the European model and the US model.

The European model was a "national" service similar to that adopted in Australia – see later – and contrasted with the "regional" US model which is outlined below. The US research was supplemented by other studies such as the Coopers & Lybrand study – see later.

With this information, the concept designed for Telecom's Mobilenet service for Australia was substantially superior to that operating in the USA and most other advanced economies.

For example, the US market was divided into service regions with two operators in each of more than six regions; a "wireline" mobile carrier associated with the landline operator competing with a "non-wireline" mobile carrier. This fragmentation of the market and other aspects of the service caused customers to have such serious concerns about the cost, markedly hindering take-up and usage.

For example, many customers left their mobile phones "off" as some incoming calls would be billed to the receiver; a customer of mobile operator "X" receiving a call from a customer of mobile operator "Y" was billed by the "X" operator for the component of the call from the "X" base station to the receiver. Customers also were also concerned about the very high cost of roaming between service providers. For example, a customer of mobile operator "X" making a call outside the home territory of operator "X" paid a very high premium. The roaming "surcharge" could be up to 80% of the call cost, and particularly deterred the business people who travelled frequently outside a home territory. Both the receiver and roaming factors resulted from the fragmented market structure and because the billing method was convenient for the carriers and increased carrier revenues.

Typically US mobile operators charged calls on the radio occupancy time (or "airtime") rather than connect time; the charging increment was in expensive 60 seconds rather than 30 seconds or less; and voicemail was usually charged for all components including mailbox occupancy and calls.

Mobilenet was established as a "national" network rather than the US "regional" concept, with a national call structure, no roaming fee, and a "customer friendly", simple and low cost billing system for settlements between carriers when competition was introduced. This approach encouraged growth and was, as intended, difficult for a future regulator to unwind when considering alternative models for competition.

The caller always paid for the call to completion, as for the landline network. This removed one objection in the US to buying the service, encouraged calling by leaving the handsets on, and consequently increased calls and call revenue.

The call structure was simple, easily understood and customer friendly. All calls were timed and there were three calling zones across the Australia – local, medium distance and long distance. In the USA there were many cellular operators, two in each service area, and each had different and relatively complex call rates.

Billing was based on connect time – the time the call was connected – rather than the longer radio "air time". In the USA the call was charged on the "radio time" which, depending on the length of the call, could be up to 10% higher.

Charging was in 30 second charging increments, rather than the more expensive 60 seconds.

The mobile voice mailbox was free. This ensured that almost every call made was completed and billed, regardless of whether the call was answered. The called party then could then make another billable call to the mailbox service, and perhaps another call again as a result.

This "generous" customer oriented concept may appear altruistic to a predatory marketer, but it appears to have been a key factor in the rapid growth of the service and set the standard for when competition arrived.

Some Other Marketing Issues

The business strategy was to drive growth to the limits and prepare for competition. The strategy addressed perhaps three main marketing issues beyond the service concept: the objections to buying the service, systems and distribution.

While the service concept was similar to those used in Europe, the strategy and marketing plans were based on the highly competitive US market.

The main objections to buying the service were the high prices of the handsets, the bulk and weight of the “portable” handsets, and the short battery life of the "portables".

The prices of the handsets were high, as much as five times today's prices; about $1,500 ($3,500/2016) for the vehicle-mounted model, $2,500 ($5,500) for the “heavy duty” shoulder-carried “portable” model, and $4,000-5,000 ($9,000-12,000) for the so-called portable model (the "Brick"). The shoulder-carried portable model weighed almost 20 kilograms and both the shoulder and fully portable models were bulky, heavy and had a relatively short battery life. Clearly a selling story had to be developed for each market segment – say early adopters, trades people, and business people – which promoted the benefits sufficient to overcome the price, bulk, weight and battery life objections.

A second serious problem was the mobile mainstream computer system for sales, order processing, activation, fault reporting and service restoration, billing, collections, customer service and customer data management. The Telecom order processing system (DCRIS) and the Customer Automatic Billing System (CABS) were too basic to be modified to match the capabilities of mobile systems already operating in the USA and Canada. Research of the mobile systems available around the world, particularly in the competitive mobile markets including those used by AT&T, GTE and Bell Canada, found that the most advanced system was that recently installed by Bell Canada called RACE (the meaning of the acronym is not known). The system was superior to any Telecom might adapt, appeared to be easily modified to requirements in Australia, and was likely to be competitive until at least 1992.

The system offered all of the required components of a mobiles system in a competitive market. Crucially important, it allowed access, equipment and call packages to be introduced quickly as conditions changed in the market, fast changes in call charges, and would support the very high growth rates expected for the mobile service. It could also produce bills in different formats for third parties such as distributors and agents. The US experience was that as much as 60% of services could be sold by these outlets, and airtime resale could be required by an Australian regulator when appointed.

RACE was years ahead of other similar systems in Telecom, and was the first "product" system in Telecom to provide all of the product functions in one suite. Unlike the DCRIS/CABs option, it did not use scarce Telecom systems people who were needed for other urgent systems development in Telecom.

A problem was that RACE was yet another mainstream computer system in Telecom – others included DCRIS/CABS, directory publishing, and DDS/AUSTPAC (for data). Until RACE was replaced by a superior Telecom system or CABS was modified, customers would receive at least two bills – one for the fixed telephone service and one for the mobile service (and possibly another for data) – initially printed in slightly different formats.

The conversion to Telecom's requirements and installation was completed on time and slightly over budget, which was an unusually good result for computer systems development of this scale in Telecom or any business at that time.

The Strategic Assumptions for the Cellular Service

Noting the narrow escape from network deregulation after the Davidson Inquiry in 1983, the limitations of the PAMTS system in the market, and the how far behind Telecom was in deploying a cellular service, a number of strategic planning decisions were made to design, launch and rollout a cellular service in Australia.

Observations of the mobile market in the USA and strong business contacts with a number of landline and mobile operators in the USA – including AT&T, some of the Regional Bell Operating Companies, (Southwestern Bell Mobile and Bell Atlantic Mobile), GTE and GTE Mobile – concluded that the US mobile market was one of the most intensively competitive globally, ranking with such as Hong Kong and Japan.

Based on this, the strategic assumption adopted in 1985 was that the high level of competition in the USA would likely influence the Australian Government to adopt a similar regulatory model for Australia – a duopoly – and a competitor using technology and experience from the USA would enter the cellular mobile market in Australia in five years – that is, by 1990.

Put another way, Telecom had five years to build and operate a cellular service which was sufficiently strong to hold, say, 70% of the market after five years of competition.

The Drive for Competitiveness

In 1985, ten years after its creation as a separate business entity, Telecom was still basically a public service business totally unprepared for any competition, and competition was now assumed to arrive in 1990.

To achieve a rapid network coverage and quality, build a mobile business which would thrive against a competitor and perform at "best practice levels" within five years was a huge task. Mobiles staff were untrained and inexperienced in every business function except engineering, and most, even the engineers, were afflicted with the Telecom culture of complacency.

How would Telecom establish this strong market position, match a competitor, and at the same time try to negotiate a regulatory framework with as few imposed disadvantages as possible within five years?

The strategic approach was to understand what a competitive market would look like in five years, what would be the likely tactics used by competitors, and at the same time, what was world benchmark performance. This would define the standard that Telecom's mobile business must reach when the competition arrived.

Four approaches were used to attempt to transfer the skills and experience in the USA to Telecom's mobile service.

Firstly, in 1987 senior executives from Southwestern Bell Mobile Services Corporation (SWBMSC) delivered a series of tutorials to the Telecom's mobiles services people over a month. AT&T and McCaw Communications were the largest mobile operators in the USA, and SWBMSC was high in the second tier, the dominant operator in the US mid-west.

The senior executives covered the marketing, operations and engineering areas by outlining their operations, experience and plans for their market in the US. The visit proved very useful. The SWMBSC people were completely open about their business and provided a generous range of data; marketing, engineering design, construction, operations and accounting plans and processes that Telecom could adapt to make faster progress. Perhaps as important, Telecom mobiles marketing, engineering, systems and accounting people could observe first-hand the type of people with whom they would be competing, how they thought and how they were motivated.

Secondly, in 1988 Coopers & Lybrand reported on the wider US cellular mobiles market. The results are summarised later.

Thirdly, 18 months after launch, Booz Allen-Hamilton, a world leading benchmarking consultancy at that time, reported on how Telecom's mobiles business compared to the US benchmark. The results allowed sufficient time for mobiles to bridge any gaps, and are provided later in this paper.

Towards the end of 1988, within 20 months after launch, Telecom's mobile services management clearly knew the standard required and broadly how to achieve it. The results were factored into the business plans for 1989/90.

Finally, during 1991 contacts with AT&T, GTE Mobilenet and SWBMC provided briefings of their business plans, and these were used to update the business plan for 1992/93.

The Coopers & Lybrand Report

Early in 1988, within months of the SWBMSC seminars, Coopers & Lybrand (C&L) reported the results of a "Study of the USA Cellular Market".

It was understood that the while the USA was well ahead in terms of strategy, marketing, service and billing, the USA was falling behind Europe in setting and following network standards – for example, GSM, GPRS and UMTS.

The main items of interest in the C&L report which might be helpful to Australia were:

- in the USA **in the first four years of "competition"** (1985-88) mobile operators charged a high premium for the convenience of the mobile service compared to charges for the fixed (wire-line) service; the activation charge – the charge for "switching on" the handset to the radio network, the equivalent of the fixed line connection charge, the monthly access charge and the per-minute call charge were far higher. The belief was that this premium had virtually no effect on cellular growth and activations;
- cellular network activation fees and access charges varied widely over the cellular markets, but had moved little over the five years;
- operators charged very high roaming fees because customers moved frequently between the many cellular market areas – some markets charged a registration fee, a per-day charge and a per minute charge. Roaming revenues increased from 7% of total revenues in 1986 to 18% in 1988;
- the most common billing policy was airtime (the time the call occupied the radio link for the call) rather than the shorter connect-time for the call. The billing unit was commonly one minute;

- mobile operators offered a medium degree of bundling of terminals, access and call charges;
- Typically four additional features (such as all forwarding, call waiting, speed calling and emergency hotline directory listing) were offered with the basic service. Discounts were offered on the basis of the number of minutes billed per month, the number of users on an account, and the degree of competition in a market. The maximum discount on a minute basis was about 15% and on a line basis about 23%;
- the average monthly cellular bill had fallen from $141 in1984 to $92 in 1988 and was expected to drop to $60 by the mid 1990's. Apart from the effect of competition on prices and revenue over time, new customers tended to make fewer calls and more of their calls were local calls;
- by the end of 1988, after five years, carriers were covering 75% of the US population and this was expected to reach 95% by the late 1990's. The number of customers had reached 1.9 million. The service penetration was 6% of the population;
- "de facto" network performance standards were operating within the industry which would likely take another year or so to be agreed formally and promulgated;
- Ideally mobile networks were designed to allow no more than 2% of calls to be blocked at peak traffic periods, but rapid growth has caused considerably greater blocking. Similarly, the de facto standard for call dropouts was 2-3% which was regarded as acceptable; if exceeded it was assumed that there was a system or subsystem failure and an investigation was triggered by the operator;
- there were basically three types of cellular phones offered. Portable (5% of the market), transportable (a phone with a battery pack - 20%), and fixed phone (installed in a vehicle - 75%), with several variants totalling less than 1%, including a credit card phone;
- customers selected a phone mainly on the basis of cost. Average wholesale prices for phones were falling; from mid 1983 to the end of 1987: "fixed" cellular phones fell from $3027 to $1432; transportable phones from $2292 to $1734; and portable phones from $2704 to $2304;
- Retail prices of phones were now more affordable for tradespeople, business people and residential people. In January, 1988, mobile phones were advertised for as little as $350;
- 56% of customers bought a terminal from the carrier or its agent; 19% from a radio dealer, 15% from a retail outlet, 6% from an audio sound store and 11% from others;

- the carrier and its agents sold 64% of phones and network access, independent dealers and manufacturers 12%, subagents 9%, resellers 9%, and others 6%;
- to service the phone, 43 % went to the carrier or its agent;
- knowing the customer base in the market was crucial. Churn, the loss of customers to a competitor, had reached 30% in a year in some markets. The network battle was for the highest number of the most profitable customers and minimising "churn";
- SWBMSC's customer distribution by usage in 1991 was typical – see Table 1.

Table 1: SWBMC Distribution of Airtime Usage (Call Time)
The top 10% of customers contribute 45.3% of airtime.

Users (%)	10	30	50	80	90	100
Airtime Usage (%)	0	1.7	8.5	36.7	54.7	100

Source: SWBMSC, 1991

- market share depended almost totally on direct or tied distribution; the customers who are known to the operator. Customers of airtime resellers were vulnerable;
- Tied distribution insured against loss of customers due to reseller takeover, financial failure or disloyalty;
- resellers were motivated almost entirely by payments offered. The higher the influence of resellers in the market the higher tended to be the network retail prices (to meet reseller profit expectations);
- the emergence of mobile networks had driven the development of a wide range of new applications, including fixed cellular service for locations difficult or costly to connect to the fixed network, remote monitoring and sensing, security and medical alarms, coin and credit card operated payphones, fleet vehicles and data transmission.

From this report Telecom's decisions on access charges, call charges, charging (or not) for roaming, and connect time billing seemed sound to drive growth. The fall in average monthly billing and phone retail prices were compared with the assumptions in the business plan and adjusted to the extent considered applicable to Australia. Three fundamental areas needed more work: bundling of terminal and network charges including discounting; network performance standards; and distribution through resellers and agents.

Deloitte Ross Tohmatsu

In November, 1990, Deloitte, Ross Tohmatsu provided a report comparing the cellular businesses of Telecom and Bell Canada. It supported almost all of the Coopers & Lybrand study. The four levels of rate packages were remarkably similar.

The main reasons that customers in Canada chose Bell Cellular were service and coverage (53%), price (27%), reputation (7%), customer service (6%), liked the sales person (5%) and extra service features (2%). Revenue per customer per month had fallen from $108 to $93 over four years. The monthly churn rate had increased from 1.7% to 3.0% over the same period, later reaching 4%. While the two businesses had about the same number of employees, Mobilenet had half the sales representatives (118 vs 233) and 17% more technical and engineering people, primarily due to the luxury of a network monopoly.

The Main Strategic Actions

The main strategic actions taken from 1985 were textbook actions, unremarkable in the private sector.

The priority was to drive growth and match any competitor entering the market in five years to 1990. To achieve faster progress the business would adapt overseas experience, technology and systems, using the contacts in the USA as the major source of experience and information.

1. Drive revenue growth as rapidly as possible to establish a strong market position by 1990 (assumed entry of competition) and a major share

This would generate a higher cash flow and an earlier return on investment, support a dominant branding, market position and market share in the market in 1990 and beyond, and set a standard for any competitor to attempt to match.

The launch of the cellular service would be, at latest, in early 1987. This allowed three years to establish the required strong market position by 1990.

The service concept and key characteristics should be superior to those in the USA.

2. Deploy the Network to provide 90% coverage in 1990 and superior calling quality.

Comprehensive coverage, a superior call quality, network performance, and capacity would support the required high customer growth, establish a perception of superior performance and service, and achieve a dominant market position in the early years of competition with premium prices.

In overseas competitive markets two of the three most important factors in achieving the dominant position were **service coverage** – both in terms of population covered and service reach, for example, at street level and within buildings and basements – and **calling quality**. Also, to have any chance of maintaining the cellular monopoly (which was very unlikely), Telecom had to be perceived as acting responsibly by providing a rapid build-up in coverage.

Growth in coverage was limited by construction capacity and funding, both of which would be driven within the business. The growth in services was expected to be higher than in the USA, and without competition operating margins would be greater.

Coverage of 90% of the population by year five was a high-risk target. A rapidly expanding coverage and a high growth in the number of customers risked compromising the calling quality: either calls could not be connected, faded when the radio signal weakened, or terminated when the radio signal was lost. Causes included traffic congestion (calls exceeding capacity), calling beyond the service coverage, and “black spots" or "holes”, places where the radio signal did not reach. Black spots would multiply as the price of handheld mobiles fell and many more calls would be originated from handhelds within cars, buildings and other radio sheltered locations.

It was a huge challenge to build capacity in an area ahead of a rapidly increasing customer base, expand to other population centres on the coverage schedule, and quickly respond when customers inevitably discovered "gaps" in the network.

3. Adopt and deliver the US “defacto” network standards until a future regulator introduced national standards.

These seemed appropriate and would provide a reasonable rationale in negotiations with a regulator for any national standards and the handling of complaints.

4. Attempt to maintain the Call Charge and Billing Structure, although different from the US.

The key feature of the structure was that it was customer friendly and encouraged high growth and usage. While a competitor could challenge with a charging increment shorter than 30 seconds, other elements such as caller pays, connect time billing, free roaming and free voicemail could all be changed, but would be difficult for a competitor to change unless Telecom followed.

5. Because Network competition was almost certain – perhaps in 1990 – attempt to influence Government policy to minimise any negative regulatory impact on Telecom

The most likely time for a regulator to introduce competition was when Australia decided, through a regulator, the standard and launching date for the next generation of mobile technology that would replace AMPS. This technology would be digital and possibly the service proposed for Europe – General Service Mobile (GSM) – planned for the early 1990's. This timing was later than the assumption that competition would begin in 1990.

Telecom's corporate policy was to oppose network competition, but this was unrealistic.

Within that policy, and using the overseas studies as precedents, Telecom would attempt to influence the development of the new regulatory framework so that it imposed few, if any, disadvantages on Telecom. Concerns within Telecom included that the new digital technology was acceptable to Telecom; Telecom would not be required to provide air time resale to a competitor; interconnect fees for competitors and airtime reseller wholesale prices would be reasonable; Telecom would not be required to accept calls initiated by a competitor's customer outside the competitor's coverage area; and sharing sites and equipment including mobile towers with competitors would not be required.

6. Structure a strong Marketing, Sales and Customer Service capability

Noting the US experience, the priority was to drive growth and, when competition arrived, minimise churn. Logical actions followed from this, for example:

- segment the market based initially on the US experience, identifying the higher profit segments;
- develop early profit contribution tracking by customer to assist in identifying and retaining higher profit customers;
- maintain the initial service concept to encourage take-up and calling, and in the year before the introduction of competition, prepare a range of bundles of terminals with service charges and with discounts based on call minutes;
- attempt to "own" at least 70% of the customer base by confining the airtime resale customer base to less than 30%. This meant a strong sales force perhaps gaining at least 50% of the customer base and solid support for distributors and agents with services expertise, promotion and support for their sales activities. Customers "owned" by airtime resellers could be lost overnight to a competitor or through reseller bankruptcy;

- provide almost "instant" activation by 1988 to support take-up;
- provide 24/7 customer service. This would take a year or so. Initially customer service would be offered by Telecom's low productivity operator services area with full unionisation and strong resistance to change;
- monitor the RACE system to ensure it would be fully competitive, particularly its capability to identify early any market trends such as churn, which in the USA and Canada could exceed 30% in a year. Around 1990 seek a superior national computer system to support more flexible service pricing, packaging, billing and distribution to be installed nationwide within two years;
- attempt to develop a range of unique and sustainable features that would provide a competitive advantage – see later.

7. In 1988, based on the planned Booz Allen Hamilton (BAH) benchmark study, lift the customer service, operations and performance to benchmark within two years.

1988 was almost two years after launch which allowed time for the business to settle down.

The BAH study would identify gaps in performance which must be bridged before the competition arrived, assumed to be in 1990.

8. Recognising that Cellular is likely the Core business; expand into other Mobile markets that satisfy profit, market strength and other criteria

In 1985 Telecom was already providing a radio paging service and the PAMTS mobile service. Radio paging services were transitioning to digital technology, but were likely to be largely replaced by cellular mobile services over the next decade.

A number of mobile technologies were emerging or would do so in the next few years.

The cellular technology provided a large number of mobile applications as well as “fixed" cellular services. Trunked private mobile radio (TPMR) was a vehicle-fleet-based radio service attractive mainly to transport businesses. Data despatch was a low cost communication service. Land mobile satellite services offered vehicle and fixed point communications which were particularly useful in the rural and remote areas. Aeronautical mobile services could operate from planes.

CT2, a UK standard, was an advanced cordless, short range cellular mobile service which might complement AMPS. A European digital standard for short range cordless systems, DECT, was expected to be widely used for homes and wireless business systems.

Each of the emerging technologies would be monitored against several investment criteria. For example, the standard must be internationally accepted (as was GSM), the demand must be nationwide (as was TPMR and GSM), and the demand must be economic and complementary to Telecom's range of services. If the demand were doubtful or unproven, a low-cost trial might be undertaken to assess the service and demonstrate Telecom's responsiveness as the national carrier. See later.

9. Attempt to create a range of Service Differentiators which will support market leadership and the largest market share at a price premium.

A differentiator is a service feature valued by a customer or market sector that can be introduced at any time and which a competitor is unlikely to match within three months. The thinking was that with a range of features available, one or more could be introduced at times to support Telecom's price premium, accelerate demand or to counter a competitor's action.

Telecom would aim to maintain the advantages of network coverage and calling quality which would be reinforced by differentiators such as unique distribution capabilities and service offerings.

GSM, being a digital technology, offered a huge potential for developing differentiators. At the time examples might include immediate activation, immediate billing, short messaging, conferencing, user call reporting systems for business customers, Fleetswitch for vehicle fleets, find-your-phone, and personal and property security.

10. Operate the Mobile business "Independently" of and physically apart from Telecom.

All the cellular mobile businesses in the USA and Canada – SWBMC, GTEM, and Bell Cellular – operated as independent companies, to have the flexibility needed in the highly competitive mobile markets. Those associated with the Bell System and GTE were certain that to work within the parent would cost substantial market share and profits. Telecom mobiles needed the same flexibility to achieve the ambitious deployment and build-up, and to prepare for competition.

To be credibly competitive Mobile Services had to be physically separated from the Telecom public service culture. This would allow faster and more focussed improvement.

This meant that:

- the business strategy and marketing strategy would operate “independently” of Telecom’s fixed network, but take advantage of synergies such as branding and using the Telecom sales force as another sales arm;
- Noting the experience in the US mobiles market, a substantially different approach was needed for marketing mobile services compared to the landline market. For example, even without competition there would be network resale of mobile services but not for landline services. Most mobile terminals would be installed and repaired at depots while landline customers would continue to be connected and serviced by visits of technicians to premises. When competition began the churn of mobile customers was expected to be substantially higher than for landline customers;
- the mobile network would be designed and built “independently” of Telecom's landline network. This would avoid delays and limitations usual in Telecom engineering, but take advantage of synergies such as common facilities – exchanges, the marginal cost of base station back haul and property sites;
- information systems would operate "independently", particularly the adaption and operation of the RACE system, but take advantage of synergies such as computer processing centres and computer networking;
- all other business functions would operate independently of Telecom including accounting systems;
- the business should be located physically apart from Telecom and at arm’s length to attempt to eventually extinguish the public service policies as well as the culture. In time this could permit the negotiation of workplace agreements and working practices appropriate to the market and the competition, in most instances significantly different from mainstream Telecom.

Separation from mainstream Telecom and incorporation would enforce a more disciplined, responsible and accountable behaviour among the management and staff. Outside the Telecom" comfort zone" the consequences of workplace complacency and incompetence would soon be apparent in loss of market share and of employment.

In 1987 the new mobiles businesses was located about three kilometres from Telecom’s headquarters.

The eventual aim was to establish Mobile Services as a separately incorporated "arm's length" subsidiary of Telecom.

11. Implement a formal business relationship between Telecom and Mobile Services

This relationship would include "arm's length" interconnect conditions and the provision of services such as network services, computing and accommodation at commercial rates.

The aim was to attempt to minimise the negative effects of deregulation on Telecom as a whole, and to make Mobilenet's trading statement more commercially realistic.

Under network de-regulation, the industry regulator would be expected to rule on such as fees for a competitor to pay for interconnection with Telecom's landline network and for wholesale rates for resale of Telecom's capacity. With Mobilenet paying a high interconnect fee to Telecom – a rate at that time of 13 cents per minute – this might support a higher fee to apply for a longer period to interconnecting carriers.

Modelling Mobilenet

Mobilenet was a service which required extensive and continuing mathematical modelling for the business plan, the related trading statement and for the design and deployment network.

There were six main variables: the rocketing demand for the AMPS service beyond forecasts: the falling prices of the mobile phones; the transition from the AMPS technology to the GSM technology; the upgrading of the business plan after the SWBMSC seminars (1987), the Coopers & Lybrand report (1988) and the Booz Allen Hamilton benchmarking study (1988); the nature and timing of competition; and the costs of distribution -- direct, agents and resellers under competition.

Specifically, some parameters to be modelled included market demand and shares for different market entry dates of network competitors, customer bases for AMPS and GSM after the launch of GSM, both for Mobilenet and competitors, and payments to resellers and distributors to attempt to secure the customer base.

Both the growth in customers and related calls from 1987 were higher than expected each time the business plan was reviewed, and higher than experienced in other markets around the world except perhaps Hong Kong.

Booz Allen Hamilton Benchmarking Study

Information from the mobile businesses in the USA since 1987 indicated that Mobilenet was broadly on track to be competitive. As a check, Booz Allen Hamilton, a US-based benchmarking consultancy, was engaged to report on progress in 1988.

BAH reported that, after almost two years in operation, overall Mobilenet's performance was at parity with typical US performance in terms of network performance and financial performance. The service concept, including call charging, was a sound basis for network competition. One superior factor was that the calling party pays. It seemed that given the decisions taken for pricing and billing, revenue, network performance and the interconnect regime were satisfactory. See Table 2.

Areas of lower performance were daunting: that is, revenue generation; marketing costs (unrealistic when there was network competition); engineering efficiency (might save $5 million per year); customer service performance (unacceptable when there was network competition); and capital efficiency (might save up to $30 million).

Revenue performance was lower than the best US performance – $1,600 in Australia vs $1,600-1,900 per service in operation in the United States – mainly due to deliberate current policies such as 30 second billing increments, free roaming and messaging.

Marketing and sales costs were very low compared to the US due to the monopoly, and would be far higher when competition began; for example, the sales cost per customer was $100 compared to $170 in the US.

Customer service quality and efficiency were at the low end of US ranges and were unacceptable for future competition. This was due to the service being provided by Telecom's low performance and low productivity operator services. Closer to competition, a separate mobiles service team would provide a 24-hour service at high service quality and cost parity.

The construction and operating performance was clearly affected by three factors: the service was still bedding down two years after launch, the very ambitious increase in the network coverage and the high growth rate in customers.

Overall the quality of performance of the network was comparable to the US, but improving engineering efficiency might save $5 million per year, and capital efficiency could save up to $30 million.

Considering the priority for rapid growth, the related ambitious network rollout and the two years' experience in operations, most gaps in construction and operating performance would be bridged in the short term.

Parity with the US in engineering efficiency and capital efficiency could be improved by increasing the number of customers per radio channel.

All gaps demanded early and strong action, and would be bridged over the next year. The huge difference in spending between pre- and post-competition in marketing and sales was factored into the business plan for the year prior to competition, part financed by productivity improvements and savings across the business.

Table 2: Booz Allen Hamilton Study - Mobile Performance against the US Benchmark - 1988

		USA	Telecom
Sales	Sales cost per customer	$170	$100
	Commissions	$345	$14
	Marketing	$200	$150
Customer Service	% of customers with billing enquiries	8-9%	14.8%
	% of billing enquiries answered within 40 seconds	98%	12%
	Billing calls dealt with per day per operator	80-100	54
	Service hours	24 hours	8.30-5.00
Network	Minutes of use per month - Outgoing	220-225	180
	Incoming	20-35	70
	Dropped calls	1.7%	3.4%
	Target – less than	5%	5%
	Blocked calls %	1.6	2.2
	System outage mins (peak)	2.5	4.1
Engineering	Engineering and field operations – costs per SIO	$40	$183
	Field operations staff SIOs per person	6500	3500
	Development and support staff	10	25
	Plan & design engineers SIOs per person (Telecom high due to large build program)	6000	3500
	Software engineers (High in Mobilenet due to customisation of software and in-house capability which is normally left to the supplier in the US)		
	Average cost per channel	$7-9,000	$8,750
	Switching cost per channel	$2,600	$3,450
	Infrastructure (cost per base station excluding buildings)	$290,000	$260,000 - 360,000
	SIO per channel	26-33	19
	Subscribers per base station	730-1300	607
	Capacity reserve (weeks)	8	13
	Incremental capital/incremental SIOs (Mobilenet's plan to incremental capital per incremental SIOs$920 in 1991/2, $750 in 1992	$800	$1200
Capex	Capital investment per SIO (Capital efficiency, normalised for traffic patterns was10% off best US performance)	$830	$1040
Admin	Staffing: Customers per employee	1850	1800-2500

Other Mobile Services

In addition to the basic mobile telephone service, the AMPS cellular service became increasingly popular as public (cellular) mobile phones in taxis, and were successfully trialled in trains and buses and, in Sydney, ferries. Mobile fax machines became available with potential new applications in public places and offices. Automatic vehicle location and monitoring systems enabled improved security and utilisation of vehicles, particularly for fleets. Mobile point of sale terminals could be used where fixed network connection was difficult or inconvenient. "Fixed mobile" allowed remote monitoring of sensors such as those used to monitor water levels in reservoirs or security systems in businesses, warehouses and homes.

The PAMTS service launched in 1981 was continuing to operate for the peak of 14,000 customers connected, but was phased out as the cellular service became available in each area as AMPS offered superior service and portable handsets.

Telecom's radio paging business reached a peak in 1989 with over 130,000 customers and was the largest in Australia covering more than 110 major metropolitan and regional localities. Messagebank, a computerised voice messaging service, allowed storage and retrieval and immediate or delayed redirection of phone messages to one or multiple destinations. Telecom's share of the network market was 45% and paging terminals about 35%. With the success of the cellular mobile service becoming obvious, with expanding coverage and handset prices falling, new connections of pagers fell for the first time from 36,000 in 1990 to about 27,000 in 1991. The arrival of digital paging with enhanced messaging in the pager was unlikely to reverse the trend. Under open competition, the paging service was unprofitable to Telecom; any margin earned in the sale of pagers and network usage was almost soaked up by the cost of Telecom's inefficient operator services in handling the calls and overheads. After 1990 the paging business was wound down. The arrival of the short message service (SMS), a feature of GSM, introduced in Australia by all three carriers in 1994, made paging obsolete.

Trunked private mobile radio (TPMR) was a vehicle-fleet-based radio service mainly attractive to transport businesses. Land mobile satellite services offered vehicle and fixed point communications which were particularly useful in the rural and remote areas. Aeronautical mobile services could operate from planes. A business case for TPMR was developed and approved in 1990. After spending about $3 million on design and development the service was abandoned when the formation of the Australian & Overseas Telecommunications Corporation (AOTC) was announced by the merger of Telecom with the

Overseas Telecommunications Corporation (OTC). OTC's Maritime Services was already preparing to provide a TPMR service.

CT2, a UK standard, was an advanced public cordless, short range mobile service which might complement AMPS in public areas; one application was Telepoint, a low-cost phone which called through base stations located in public locations such as streets, petrol stations and restaurants. A European digital standard for short range cordless systems, DECT, was expected to be widely used for homes and wireless business systems. Telecom proceeded with a small trial of the CT2 service in 1990 costing about $2 million. The technology worked well but there were limitations. The range of less than 200 metres, the susceptibility to electro-magnetic interference, the inability to receive calls unless near the registered base station (usually the home or business), the number of rival standards available that would not interwork, and the emerging DECT standard, argued against proceeding beyond the trial. It was a disappointment for the technologists and visionaries at the time. Their thought was of a ubiquitous "Universal Mobile Telephone Service" (UMTS) perhaps based on the European "son of CT2" as well as future improvements in DECT and GSM. As is known, the widespread coverage and falling cost of digital cellular services and the falling prices and expanding feature set for cellular handhelds became a "UMTS".

An Aircraft Telephone Service was assessed for covering major flight paths between all capital cities (including Canberra) and extending north to Cairns. Telephones on aircraft would make calls automatically to anywhere in Australia and overseas charging to a major credit card. Work with the airlines on some tests indicated that, with competition approaching, their level of interest was not sufficient for Telecom to invest.

As previously mentioned, each of the emerging technologies was monitored against several investment criteria. For example, if the demand was unproven, as for the CT2 service, a low-cost trial might be undertaken to assess the service and demonstrate Telecom's responsiveness as the national carrier.

So What Happened – Regulation?

In 1988 the Commonwealth Government released a statement on the future structure of the telecommunications industry; "Australian Telecommunications Services: a New Framework". For the time being Telecom and OTC would continue with network monopolies and the customer premises market and the value-added services market would be open to competition. A new industry regulator would be created which would ensure maintenance of standards, fair and efficient competition in open markets and the efficiency and accountability of the monopoly carriers.

In 1989 legislation created a common carrier licence for the landline line market including all telephony and broadband based public services and private networks, with Telecom granted a licence. The licence confined Telecom's monopoly to the public switched network and the conditions under which the monopoly would operate. The significance of the licence was that other such licences could be granted in the future. From 1989 others could compete for any services other than the public switched network such as value added services and the emerging internet type of services. The Act also created a regulator (AUSTEL).

AUSTEL began regulating the market in 1989 and held a number of inquiries. The "Inquiry into the Implications of Licensing an Additional Network Operator for Cellular Mobile Telephone Services" recommended that GSM would be the digital cellular standard for Australia, and that there should be two licences issued for digital cellular networks in addition to Telecom. The reason for selecting GSM standard was that it was the only 2G technology that at the time could, by design, support more than two operators. AUSTEL concluded that a duopoly was insufficient to achieve a satisfactory level of competition. The "Inquiry into The Best Means of Introducing Public Access Cordless Telephone Services to Australia" recommended that there should be no limitations on a service provider other than technical standards and radio spectrum.

Related outcomes of legislation and regulation in 1991 were:

- the establishment of the Australian and Overseas Telecommunications Corporation (AOTC - later Telstra) in 1992 with the merging of Telecom and the Overseas Telecommunications Corporation (OTC);
- the granting of licences to Optus for landline and mobile network services and to Arena for mobile network services;
- AOTC was required to permit Optus to resell AOTC's landline services and Optus and Arena to resell AOTC's mobile services from 1992 with wholesale rates to be determined by AUSTEL;
- Optus and Arena could begin marketing of GSM mobile services on their own networks in 1993 with rates for interconnection with Telstra's networks to be determined by AUSTEL;
- if a review assessed the 1989 de-regulation a success, full-scale competition would be introduced by 1997;
- to make the two new mobile licences more attractive to bidders and to release radio spectrum, Telstra's AMPS network would be shut down when the three digital networks had sufficient coverage, so as not to disadvantage analogue customers.

Although Telstra could have provided GSM services in 1992, and was the first operator outside Europe to join the GSM club, in order to create a "level playing field" Telstra was constrained from offering GSM services until 1st April, 1993 when Optus was expected to be ready. Telstra was required to again delay its launch until 23rd April to meet the government's interception requirements.

Optus began marketing by reselling Telecom's network services in June, 1992, and services on its own fixed and GSM mobile networks around May, 1993. Arena (later known as Vodafone) entered the GSM mobile telephone market later in October, 1993.

Until the decision was made to issue two landline carrier licences and three mobile carrier licences Telecom's public position was that the landline and mobile monopolies should continue for several reasons, including the funding of the Telecom's service obligations (CSO's) and the importance of support for local manufacture. In fact Telecom's (and later Telstra's) real concern was that when, inevitably, competition was introduced, Telecom would not be disadvantaged by requirements such as funding of CSO's, providing resale capacity to competing carriers, unreasonably low interconnect charges and wholesale prices charged to competitors, future relationships with unions and government, or be impeded in expanding into overseas markets.

Telecom advocated GSM as the new mobile standard. Except for some Telecom insiders, the third mobile licence was a surprise, and all within Telstra were unprepared that the mandated closure of AMPS on 1st January, 2000 as an incentive to Optus and Arena. There was also some concern that the interconnect rates and wholesale prices for resale were too low.

The extraordinary gift of resale of the AMPS network to Optus and Arena was potentially very damaging to Telstra. Without one dollar of investment in a mobile network – a network in which Telecom had invested about $1 billion – all a competitor needed to do was offer Telstra's mobile customers a discount to transfer, with the potential of gaining perhaps 20% of the market within the first year or two.

Telstra was not required to share base station or to provide backhaul transmission. Wholesale domestic mobile roaming – for example, an Optus customer in an area not covered by Optus, being able to use the Telstra network – was also not required.

Apart from the regulatory arrangements for the new telecommunications industry, it is interesting to note the wide range of other regulations and regulators that Mobilenet managed at the time. These included standards, spectrum, trade practices, prices surveillance, privacy, environment (base stations), brain damage from use of handsets and consumer affairs.

So What Happened in the Business to 1991?

Telecom's cellular mobile service, Mobilenet, was launched in Sydney in February, 1987.

The service was billed separately from the landline services, and unlike the landline bills, provided full itemisation of calls.

The handsets were clumsy, heavy and expensive for the times; about $1,500 ($3,500/2016) for the vehicle- mounted model, $2,500 ($5,800/2016) for the “heavy duty” shoulder-carried “portable” model, and $4,000-5,000 ($9,000-11,500/2016) for the hand-held "Walkabout" model. After one year the percentage of portable (hand-held) phones being used in Australia was 20% compared with Hong Kong 80% and the USA 10%.

Mobilenet’s rollout of coverage was very fast, a triumph for Telecom's mobile network engineering group. Mobilenet was operating in Sydney in February, 1987, and Melbourne in May, 1987. By June, 1988, the service was operating in all capital cities except Perth and in 10 regional areas; there were over 30,000 connections, and sales exceeded 2,000 per month; Perth was covered several months later. In the first ten months the number of cellular services in Sydney and Melbourne exceeded those sold nationally on the PAMPTS network over the preceding seven years.

By the end of 1988 it was clear that competition would not begin in 1990 as assumed, but likely three years later. Also clear was that the strategic aim of 90% coverage was impractical. Telecom continued to rapidly expand the network. After less than four years, in June, 1991, coverage reached 77% of the Australian population; most of the regional towns were covered as were most of the intercity highways. It was possible to drive from Bundaberg to Melbourne along the Pacific and Hume Highways and never be out of telephone contact. Mobilenet was thought to provide the longest corridor of cellular coverage in the world.

In June, 1992, the number of services exceeded all forecasts, particularly among small and medium business customers, reaching 440,000, coverage exceeded 84% and call quality was at benchmark.

In January 1992, the Mobilenet network was reasonably well prepared for competition. New customers were connected to the network within 30 minutes for six days a week (Sunday trading was yet to come). A range of “Flexi-Plan” tariffs combined various combinations of access fees and discounted call charges provided customers with greater control over calling costs. Call tariffs were simplified from three charging periods to two; “peak” and “off-peak”. A 24 hour a day customer service was operating seven days a week.

Untested was Telecom's skills and experience in competition against Optus and Arena (later Vodafone).

Table 3: Analogue Cellular Radio Networks - Size & Penetration - 1985-1991

Source: World Bank, Collection of Development Indicators

Country	Number of Customers		Penetration Rate per 1,000 inhabitants - 1991	Year of Launch
	30.6.1985	30.6.1991		
Australia		291,459	17	1987
Canada	12,000	775,831	28	1985
Denmark	46,100	175,943	34	1981
Finland	67,639	319,137	52	1981
France (RC2000 system)		375,000	7	1985
Germany	1,080	532,251	7	1985
Italy	6,415	568,000	10	1985
Japan	61,800	1,378,108	11	1979
New Zealand		72,300	21	1987
Norway	63,075	196,828	55	1981
Sweden	73,000	568,200	66	1981
United Kingdom	5,000	1,260,000	22	1985
United States	340,213	7,557,148	29	1983

Table 4: Growth in Telecom's Mobile Service (Mobilenet) - 1987/93

Source: Australian Telecommunications Corporation Annual Report, 1991.

Year ending 30 June	1987	1988	1989	1990	1991	1992	1993
Cellular Mobile Services in Operation	4,423	31,622	94,529	184,943	291,459	440,000	635,000
Cellular Mobile Call (millions)	3.1	27.9	74.0	156.0	158.3		
Coverage of the Population (%)					77	84	

After four years the growth rate of Mobilenet services was one of the highest in the world, having regard for the small population, the distances to be covered, and the rate of deployment required to cover the capital cities and highways. Table 3 shows the year of launch, customer base and rate of penetration of analogue cellular networks for range of countries to 1991. Table 4 shows the growth in mobile services in Australia to 1993. Between

January and June, 1991, the penetration of cellular services in Australia rose from 15.2 to 24 services per 1,000 population.

Rapidly expanding coverage and the high growth in the number of customers risked compromising the calling quality; either calls could not be connected or were terminated when the radio signal was lost. The engineers had a challenging task increasing the coverage area, raising the capacity where traffic congestion emerged and filling in the “black spots".

An Evolution of the Cellular Mobile Phone

Top left: PAMTS in-car unit with the (white) cabin handset; Top centre, right & middle row left: AMPS units; Middle row 2nd left: Mitsubishi Walkabout - the first AMPS hand held; Front row first four: GSM handsets; Front row 5th from left: Qualcomm QCP860 - the first CDMA hand set.

During the first four years of operation of the AMPS service terminal prices plummeted due to the economies of scale and the effect on unit prices, and was one of the main drivers of network growth. Network competition after 1991 would likely lead to some cross subsidisation from network revenues of terminal prices, offering customers an even lower entry price to join the service, likely accelerating the already high network growth.

In 1989, within two years of launch, Mobilenet was profitable – see Table 5. Mobilenet and the basic telephone service were the only network services within Telecom to achieve profitability during the 1980's. The data services incurred losses over that period with DDS making a profit for the first year in 1989/90. ISDN was launched in 1987 and by 1990 had accumulated losses exceeding 90 million.

By the end of 1991 it was clear that mobile services would be a strategically crucial profit stream for the new Telstra - see Table 6.

Table 5: Telecom's Product Accounting Results - 1989/90

Source: Finance & Accounting

	Revenue	Expenses	Contribution ($millions)	Non- Attributed Overheads	Net Contribution
Telephone Service: Basic Access, Local Calls, STD calls, International Calls, 008, National Operator Assisted International Assisted	5858	3868	1988	614	1372
DDS	271	204	67	31	35
AUSTPAC	46	120	74	11	85
Leased Lines	304	28	20	40	19
ISDN	4	45	41	4	45
Mobiles Network	259	138	120	21	99
Directory Publishing	557	299	257	30	228
Grand Total	**8,823**	**7,531**	**1,293**	**888**	**1,293**

Note that the product accounting data was controversial within Telecom, with many product people reluctant to accept the methodology and results. 1989/90 was the first year that DDS broke even and the year that the ISDN service was launched.

The Mobile Services Business transferred to Telstra in 1992

AOTC (later Telstra) was established in 1992.

The mobile business handed over to AOTC was a strategically strong and profitable platform for the future:

1. the projected trading performance over the five years to 1997 was strong – see Table 6. Although competitors would begin network resale in 1992 and network competition in 1993, revenue was expected to increase from about $600 million to almost $1.3 billion in 1997. More significantly, projected profit was planned to rise from about $115 million to about $0.4 billion over the same period. Return on Assets would grow from about 17% to about 40%;

2. the projected product and service range and service levels appeared competitive;

3. market positioning and branding seemed strong.

However, while the mobile network appeared overall to be competitive, there appeared to be four potential weaknesses:

- the potentially very damaging requirement that the competitors must be permitted to resell Telstra's AMPS network at a low wholesale price determined by the regulator. This might result in a loss in market share exceeding 20% in the first few years;
- Telstra's marketing and sales skills and experience had yet to be tested against the two competitors;
- the distribution system of agents and resellers was not as solid as in the USA;
- a nationwide standard and world parity mainstream computer system would likely be needed to replace the RACE system about 1992.

Table 6: AOTC Mobile Communication Services - Business Plan - 1991/97

Source: Enterprises Division Business Plan - 1992/97

Year ending 30 June	1992 Budget	1993	1994	1995	1996	1997
		––––––––Plan––––––––				
		($ millions - future prices)				
Revenue	595	829	985	1,110	1,110	1,348
Expenses	480	585	669	771	867	935
Profit	115	244	315	339	372	413
Capital Additions	166	176	187	223	204	239
Assets (WDV)	533	470	534	602	627	682
Staff (EOY)	1,015	1,210	1,224	1,334	1,449	1,521
Ratios						
Revenue Growth (%)		39	19	13	12	9
Profit/Revenue (%)	19	29	32	31	30	31
ROA (%) (3)	17	35	40	38	40	41

Notes: **1. Dated September, 1991.**

2. The complete mobiles product & service range including PAMTS, AMPS, GSM, analogue & digital radio paging, Messagebank, CT-2 and PCN.

3. ROA - Profit before Interest and after Tax/Total Assets.

4. Resale of Telstra's network by competitors is assumed to begin early in 1992.

5. Network competition is assumed to begin in mid-1993.

6. The "Contribution" of $99 million in Table 5 is not directly comparable with the Profit in the above table. There are differences in accounting rules, and the Table 6 figure results from some asset revaluations and write-offs due to competition beginning in 1992.

What Happened after 1991?

Optus began reselling Telstra's AMPS network in July, 1992, offering an incentive and lower access and call charges to encourage churn.

Within two years Optus achieved a market share of 34% which, together with a low regulated wholesale rate imposed on Telstra, was highly profitable with minimal capital investment. That market share was almost 4% higher than the share that Optus holds today some three networks and 22 years later. Arena, later Vodafone, chose not to accept the regulator's resale gift, and instead focussed on marketing its GSM network. As a result, with GSM proving to be difficult to sell in the early years, Vodafone took 10 years to reach its peak market share of around 19%, a share that Optus achieved through resale in 13 months.

In April 1993 when Telstra launched its GSM network there were 635,000 analogue mobiles in Australia, and less than 4% of people had one. Almost all of the mobile traffic was voice.

Telstra continued to sell on the AMPS network – as did Optus – until GSM arrived in each area.

Problems with GSM in the first few years were so serious that it was more than four years after launch – until July 1997 – for the number of customers on all three GSM networks to equal the number on the AMPS network. The early performance of GSM phones was inferior to the AMPS phones; many phones provided poor audio quality and had a much shorter battery life. The coverage area of a GSM base station was far less than an AMPS base station; instead of the signal progressively fading as with AMPS, the GSM digital signal failed abruptly. Many customers trading "up" to GSM quickly switched back to AMPS.

The AMPS network at its peak had over 1 million customers. A condition of Telstra's licence was that the AMPS network close by the year 2000. As that time approached customers who appreciated the wider coverage area of AMPS, particularly those in regional areas, pressed for an equivalent digital service. Telstra was required to deploy a digital service based on the US CDMA standard to match the coverage of AMPS. The CDMA network was launched in September 1999 and was popular outside of the capital cities because it covered much greater areas than any of three GSM networks. CDMA grew to cover over 1.5 million square kilometres and 98% of the population. It had considerably broader reach than any other mobile network at the time. The CDMA network reached a peak of 3,000 base stations supporting 1.7 million customers (about half in rural areas) in June 2006. As required, the AMPS network did close in 2000.

The Australian mobile phone market reached 1 million in 1994, 2 million in 1995 and 3.6 million in 1996 (2.6 million AMPS). In 2000 the number of mobile phone accounts had reached 8.5 million, compared to around 10.6 million fixed lines in use. By December 2002 that had increased to 12.5 million mobile phone subscriptions, with 72% of all households having access to a mobile.

In 2010 there were more mobile services than people in Australia. Customer penetration rates were about 125% of the population. In June, 2016 it was reported that there were 32.9 million mobile accounts.

Looking Back

Three thoughts about Telstra's mobile services business from 1992 come to mind.

Firstly, deployment of the cellular mobile service demonstrated, yet again, the value of competition. Although the growth rate was high under a monopoly, the growth exploded with competition and falling handset prices.

Secondly, whatever Telstra's loss of share of the mobile market in the first few years of competition, mobile services grew to be financially crucial to the corporation. In 2016 mobile services revenue reached $10.4 billion at a 42% EBITDA margin, almost 30% of key product revenue and higher than the revenue for every other key product. (Telstra, 2016).

Telecom's 1991 mobile team can't claim any credit for that, but it at least provided a sound start.

Thirdly, Telecom's mobile team at the launch in 1987 anticipated that this new class of service would have a huge demand – mobile phones and services, fixed mobile services, Dick Tracy type wrist phones, and so on. However, the team had a very limited understanding of how far the mobile trend would develop. The team had yet to experience the internet or apps.

By the end of 2016, both Optus and Telstra were expected to provide 98% population coverage, while Vodafone already provided about 96% metro population coverage. By early 2016 smartphones – different from the 1987 dumb phones – approached a penetration of 89% in Australia, and about 60% of survey respondents have a tablet. 34% of Australians do not have a landline (ACMA, 2014). Smartphones, and to a lesser extent tablets, have become central as a means of accessing the internet and are beginning to dominate e-commerce, accounting for about a third of e-commerce transactions (Paul Budde, 2016). Australians are said to check their mobile on average 14 times a day. 68% of Australians access the internet using three or more devices (ACMA, 2014).

These devices appear to be integral to how Australians live, organise and enjoy their lives, whether socially, professionally or personally. More than half the population check their smartphone within 15 minutes of waking, interacting continuously throughout the day without being prompted until disconnecting and switching off for the night (Deloitte, 2015).

A Telstra survey found that 50 per cent of Australians feel panic stricken within five minutes when they think they have lost their mobile phone; 25 per cent panic after less than a minute. Nearly half of Australians rank mobile phones as the innovation they value the most, more than the desktop computer, laptop or microwave oven.

In 1987 the Telecom mobiles team didn't forecast much of that.

In Conclusion

The managers and staff of Telecom's mobiles services business worked outside the mainstream of Telecom to accelerate the launch of a new, superior cellular mobile service, to build a business which approached world class and would thrive when competition was introduced.

The key people included the manager, John Dearn; the network engineering manager, Kevin Phillips; the strategy manager, Reg Coutts; Peter Higgins and Tim Herring in marketing; and John Stanhope in finance.

Kevin Phillips, the leader of the mobile services engineering team, has a claim to be a prominent pioneer in mobile services development in Australia. He was important within Telecom and the industry in advocating the GSM standard for the digital cellular technology. He and his team designed and drove the very rapid deployment of the AMPS network, the transition from AMPS to GSM and the introduction and deployment of CDMA as the AMPS network was phased out. In fact the engineering team's achievement was remarkable: a very rapid roll-out in a population concentration lower than Europe and North America and on one of the world's largest land masses; an analogue mobile network which achieved a higher penetration in four years than any other advanced country except in Scandinavia, and in the last two years began to overlay a digital cellular network which was ahead of any in North America. The engineers were strongly supported by their commercial and financial colleagues.

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The Seymour-Bendigo Pole Route

Simon Moorhead

Ericsson Australia & New Zealand

Summary:

A fascinating paper from 1952 describing the construction of an aerial trunk route and the problems associated with organisation of staff, equipment and materials.

Introduction

Wooden poles were the mainstay of the telephone network in the early days; however in the USA numerous people including elected officials and newspapers ferociously opposed the erection of telephone poles. They argued that telephone poles were ugly and characterised telephones as playthings of the rich. (Bliss 2008)

By 1901 however, Australians had accepted the importance of communications and Section 51 Sub-section (v) of the Constitution of Australia gives Parliament the power to legislate on "postal, telegraphic, telephonic, and other like services". These powers were used to merge the colonial mail systems into the Postmaster-General's Department (PMG). This body was responsible for telegraph and domestic telephone operations, as well as postal mail.

The historic paper (Quirk 1952) features the construction of the Seymour to Bendigo pole route by the PMG and the problems associated with organisation of staff, equipment and materials. This route was part of a plan to provide additional circuits between Bathurst and Seymour as back up to the main Melbourne to Sydney trunk route, which follows the main railway through Albury, Wagga, Yass and Goulburn.

The paper details the physical pole configurations to support 12 channels and the selection process to decide the best route. A survey party accurately measures the path and decides the optimum pole positions and transitions to limit cross-talk, once the route is fixed and cleared. These are documented in field books which lines personnel use to plan the construction work.

This project is typical of large scale trunk works at the time which were undertaken by camping parties due to the difficulties of obtaining suitable accommodation in towns. A typical camp would cover approximately 50 kilometres of the pole route and house approximately 40 men in tents. The paper provides details of the amenities in camp including water and electricity, reticulation, cooking and eating facilities, as well as drainage and waste disposal.

ISSN 2203-1693. Copyright © 2017 http://doi.org/10.7790/ajtde.v5n1.90

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The historical paper

CONSTRUCTION ASPECTS OF THE SEYMOUR-BENDIGO POLE ROUTE

V. Quirk

Introduction

The existing telephone traffic between Melbourne and Sydney is carried by an open wire pole route of approximately 575 miles in length, generally following the main railway line through Albury, Wagga, Yass and Goulburn. At present there are operating on the route nine 12-channel systems (eight Sydney-Melbourne, one Sydney-Canberra and one Melbourne-Canberra) and a maximum of twenty-four 3-channel systems, mainly used for intra-state traffic. This represents the maximum carrying capacity for through circuits.

In anticipation of this stage, plans had been prepared for the provision of additional circuits by means of a new pole route between Seymour, in Victoria, and Bathurst, in New South Wales, pending the installation of a direct Sydney-Melbourne underground cable. The pole route, which is now nearing completion, passes through the large country country centres of Bendigo and Echuca in Victoria and Deniliquin, Jerilderie, Narrandera, Wagga, Temora, Young and Cowra in New South Wales, and, in addition to providing interstate circuits, enables substantial traffic relief to be given to these and other centres in northern Victoria and mid-western New South Wales. The open-wire route connects to existing 24 pair 40 lb. star quad carrier cables at Bathurst and Seymour, from which points the open-wire circuits are extended to Sydney and Melbourne respectively by cable carrier systems.

Because of the long distances involved the pole route was designed on the basis of maximum 12-channel carrier system capacity, a typical pole plan being shown in Fig. 1.

Accommodation of the twelve 12-channel systems on the three major trunk arms required intensive transposing of the pairs, and at the same time it was necessary for the pole spacing and wire sags to be maintained within close tolerances. In the present paper a description is given of the construction of the Seymour-Bendigo section, which is typical of the route as a whole.

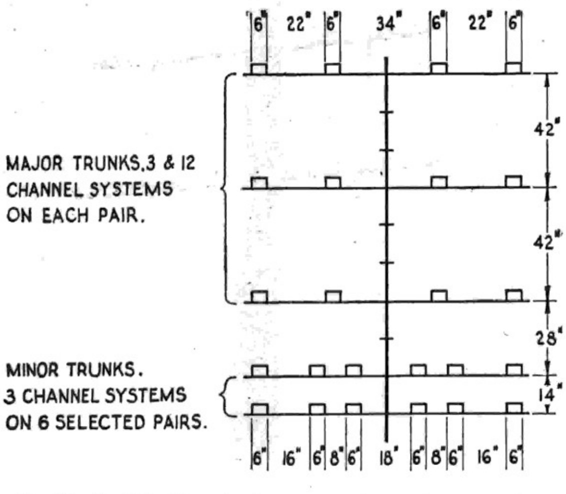

Fig. 1.—Pole Plan, showing ultimate number of pairs.

As shown in Fig. 2, the pole line, which is 56 miles in length, crosses the Goulburn River at Seymour, proceeds across country to Heathcote, and then follows the Kilmore-Bendigo highway, via Axedale, to Bendigo. Except through the Heathcote forest, where bush fires are a danger and steel H-beams are used, the poles are wood. For the steel beam construction 6" x 5" H girders are used for the normal pole height of 28 feet with 8" x 6" H girders where higher poles are required at road crossings, etc. Initial requirements were for four pairs of wires and as an additional four pairs were planned within two years, two pairs have been erected on each two arms in one and four positions on the pole, thus simplifying the subsequent erection of the additional pairs. In order to confirm the suitability of the transposition design for the route, a test E-section 6.4 miles in length, and including the twelve pairs of wires on the three 12-channel arms, was erected at the Bendigo end of the route. A general view of this test section is shown in Fig. 3, a close up view of a typical transposition pole being shown in Fig. 4. The following worst values in db of far-end and near-end crosstalk to 143 kc/s were obtained from all combinations of the twelve 12-channel pairs.

	Far-end	Near-end
Minimum	64	45
Average	74	57

Preliminary Work

Construction of new aerial trunk routes suitable for the operation of multi-channel carrier circuits involves consideration of the following:—

(a) choice of route,
(b) layout of route and preparation of field books,
(c) procurement and storage of material.

These matters must be attended to well in advance of commencement of the actual construction work.

Choice of Route: In the selection of a new route, three possible alternative locations need to be considered, namely:—

(a) along a public road,
(b) in a railway reserve,
(c) in private property and Crown land.

The railway reserve has the advantage of enabling shorter poles to be used because the minimum clearance of the lowest wires above ground for routes erected in a railway property is 8 feet, compared with 12 feet on public roads. This results in a lower capital cost and in greater ease in procurement of poles. Also, there is usually a

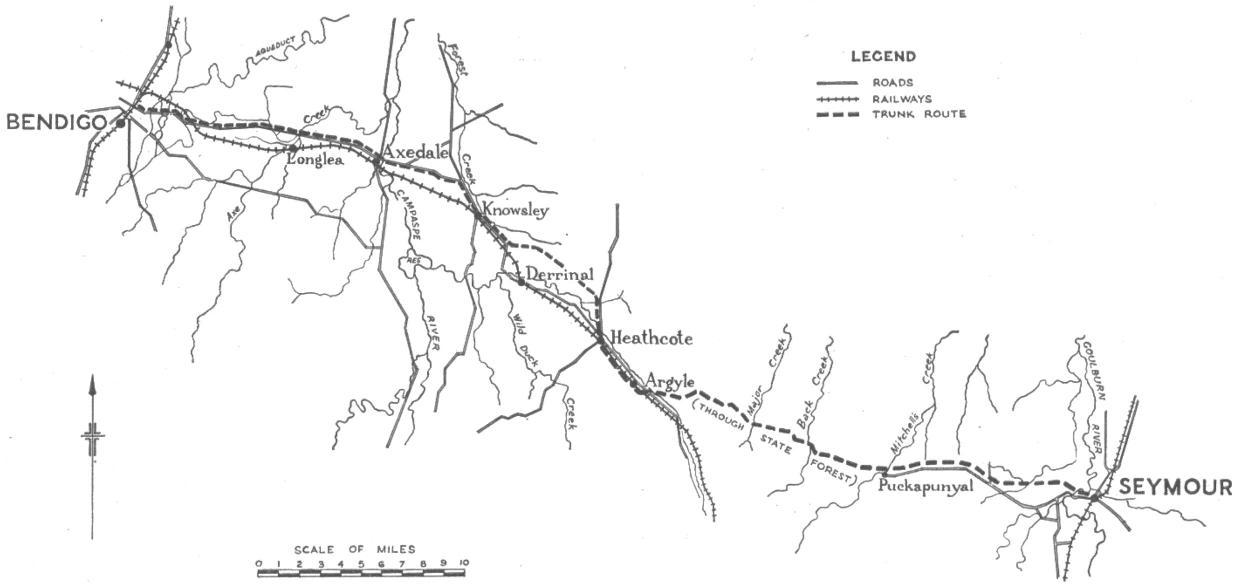

Fig. 2.—Location of aerial route between Seymour and Bendigo.

minimum of clearing. A disadvantage is that there is often difficulty of access both for construction and subsequent maintenance, in that a railway line is often some distance from good roads. The reserve itself is seldom suitable for motor traffic, particularly in the wet season, and it is often necessary to use pole trains and railway trolleys for transport.

Construction on public highways has the advantage of easy access, but often has a number of serious drawbacks. Chief of these is generally the necessity for extensive clearing. Many roads have trees growing over the full width between the carriageway and the fence line. Apart from any aesthetic considerations the cost of clearing is a major item, the felling, cutting up and stacking of timber and the burning of debris accounting for an appreciable proportion of the labour costs. The possibility of alterations to road alignment must also be taken into consideration. The presence of power lines restricts the selection of road routes, and often results in costly alterations to power construction to maintain adequate clearances between trunk and power lines, particularly at vehicular crossings.

Fig. 3.—General view of test section on Seymour-Bendigo route, near Bendigo.

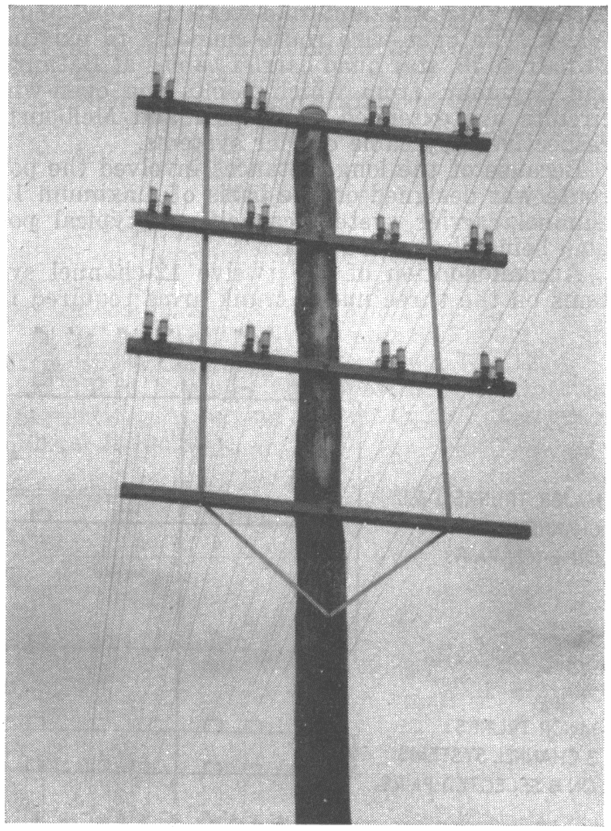

Fig. 4.—Transposition pole on test section on Seymour-Bendigo route, near Bendigo.

The route on private property combines some of the advantages and disadvantages of the roadway and railway routes. The private property route is generally more accessible than the railway route, but less accessible than the roadway route. On the whole clearing in private property is much less of a problem, but difficulties arise from possible damage, and from interference with the rights and activities of the owner. This is particularly so where the land is cultivated, as poles and stays present an obstacle to the cultivation and harvesting of crops. In addition, in wet weather private property often involves serious problems of access for construction and maintenance work, due to the bogging of pole hole borers and trucks.

The Seymour-Bendigo route provides examples of all the various route locations, including Crown land. The latter includes a military reserve at Puckapunyal, but consists mostly of the State Forest at Heathcote, where steel beam poles were used because of the fire risk. The standard clearing of 40 feet on each side of the pole line was provided, as shown in Fig. 5, but fortunately the forest is of red ironbark, which is not a particularly tall tree and the amount of clearing was not excessive. Due to the unsuitability of much of the land for cultivation in the sections where it was necessary to construct the line on private property, it was practicable to construct most of the pole line 40 feet inside the fence line, resulting in a considerable saving in clearing costs and the avoidance of public criticism which might result from the cutting of trees along the roadway.

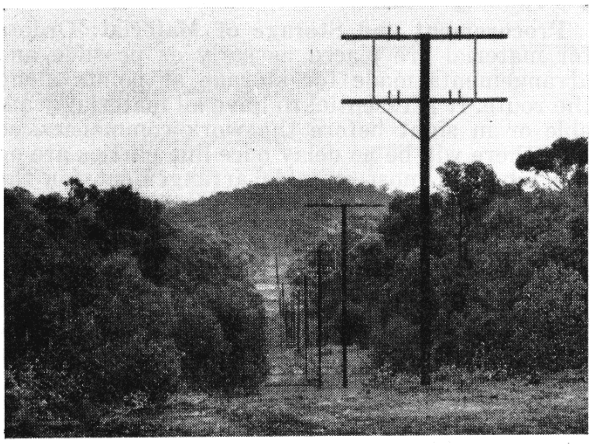

Fig. 5.—Seymour-Bendigo route, showing extent of clearing.

Where a route parallels a fence line, the separation from the latter is governed mainly by the clearing necessary and the overall width of the road reserve. Other factors which need consideration are the location of all ground stays and the presence of any power parallels. The usual margin on public roads is 5 to 10 feet, on private property 20 to 40 feet, whilst the location on railway reserve is affected by the height of the pole line, because of possible damage to the railway rolling stock should a pole fall over. The extent to which clearing was reduced by erecting the route on private property instead of along the road is shown in Fig. 6. A view of the route crossing the Campaspe River is shown in Fig. 7.

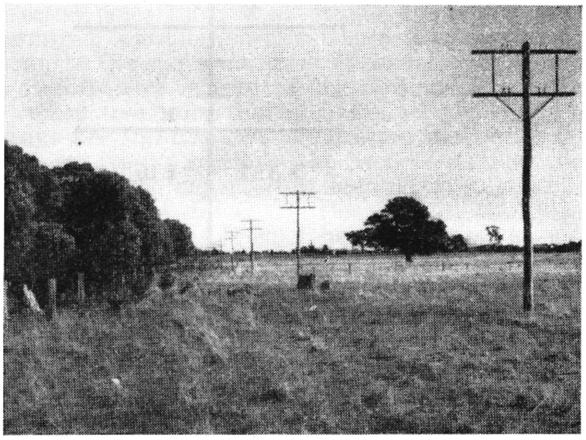

Fig. 6.—Seymour-Bendigo route on private property.

When the general location of the route has been decided upon, consultation is necessary with all public bodies and private citizens affected, and wayleaves and other matters determining the exact location and the construction of the route must be attended to.

Layout of Route and Preparation of Field Books: As soon as the final location of the route is fixed, any necessary clearing is done using a bulldozer where possible. This simplifies the work of the survey party, which makes an accurate measurement of the route, locates pole positions with wooden pegs, and takes levels for grading purposes. During the survey field notes are prepared, which, with the pole sizes as determined later from grading sheets prepared in the office, staying data, and any special provisions decided

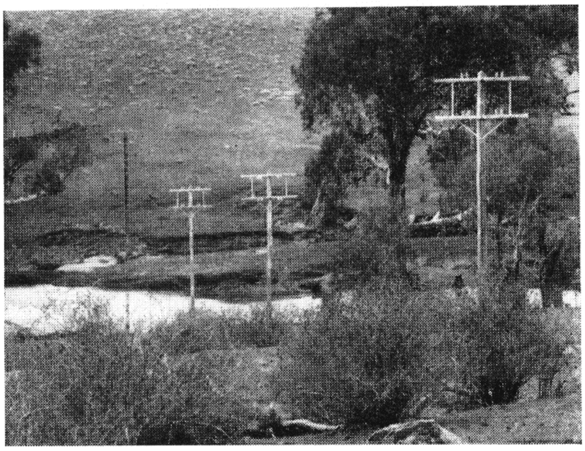

Fig. 7.—Campaspe River crossing at Axedale.

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upon by the Engineer in charge of the work, are used to prepare the field book. See Fig. 8. As several copies are required and the time taken to prepare them by hand is considerable, a trial was made of photostat copies printed and bound by the Drafting Section to form field books similar to the standard book. These have been successful, but a further improvement has been effected in in the Trunk Planning Division by use of the Fordigraph process. This is a duplicating process in which various coloured inks can be used. The latest field books are cheaper and faster to produce, and have the great advantage of being printed in colour. They are similar in size and quality of paper to the standard field book, and have strong manilla covers. The usual number of copies prepared for a job is six.

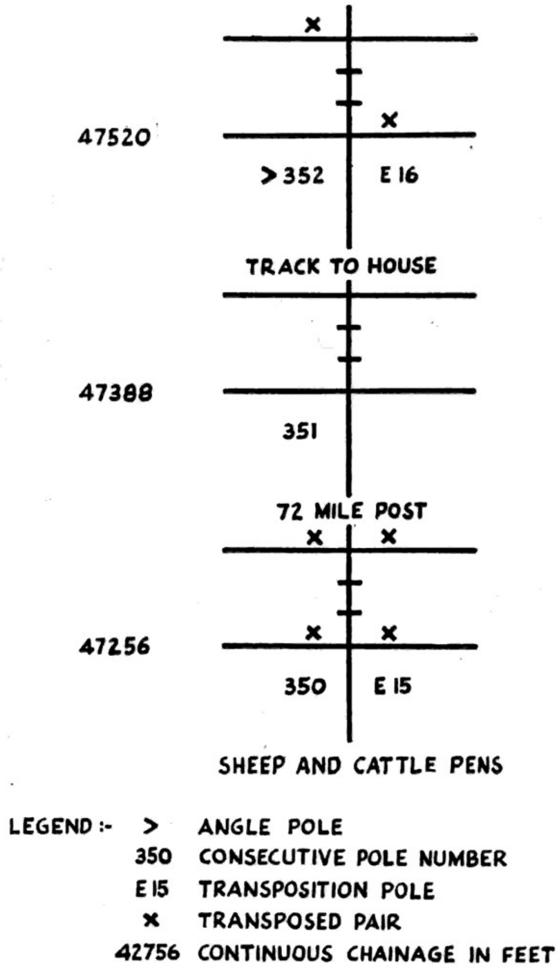

Fig. 8.—Field Book—typical sheet.

NOTE.—A covering sheet would be prepared for each field book, indicating generally the work to be carried out. In this case the work consisted of erecting 4 pairs of 200 H.D.C. wires in pin positions 1.3-1.6 and 4.3-4.6. Where only the basic pole layout is shown as for pole 351, the wires would be erected in the correct pin positions, but would not be transposed.

In the field books the poles are numbered consecutively, as well as in accordance with the transposition scheme, to correspond with the numbered pegs set up in the field by the survey party. The pegs are made of jarrah or red gum, and are approximately ten inches long. Angle pegs are made of 3″ x 3″ timber and painted red. Pegs for straight line poles are of 2″ x 2″ timber, painted yellow for transposition poles and white for other poles. Where transpositions occur at angle poles a yellow peg is placed alongside the red peg. Identification of the survey pegs in this manner and indication in the field books of all prominent land marks, and features including mileposts, gates, houses, dams, etc., as well as pole chainage, simplifies the task of the line parties when work commences, and minimises the possibilities of mistakes in laying out poles and subsequent fitting of transpositions. In addition to pole and transposition identification numbering, pole heights, pole plans, description of work to be done, and the geographical identifications, power crossings are included in the field books. The last item is of assistance in ensuring that standard clearances are effected, and in taking safety measures during the running of wire.

Procurement and Storage of Material: Orders for material are placed as early as possible and arrangements made for storage at points along the route. It is essential to have all material available or in sight before the work commences, so that there will be no delay once line parties are on the job. The most suitable arrangement for the storage of material is to have huts erected at line depots along the route so that material can be accepted and stored as it becomes available. Poles are delivered to pegmarks, or to dumps along the route and laid out from there. Huts have recently been obtained which are particularly suitable for the storage of material on large jobs. They are made of angle-iron frames bolted together, and covered with corrugated iron sheets attached to the frames with metal screws and clips. The roof is of the gable type. The whole unit is simple and speedy to erect and dismantle, and presents no difficulties in transport. Two sizes are in use, 20′ x 10′ and 8′ x 10′.

Construction Work

When the preliminary work has been completed the route pegged, field books prepared, material including poles procured, and accommodation arranged for staff, the actual work of construction commences. The first consideration is the laying out of poles to pegmarks. On the Seymour-Bendigo job the wooden poles were tank creosoted at Rushworth, and delivered straight to peg marks by Departmental pole trailers, the officer in charge at the creosote plant being provided with a field book showing peg numbers and corresponding lengths of poles, so that poles could be loaded for economical laying out along the route. Where poles are delivered by rail to sidings, a mobile crane has proved most useful in loading the poles to pole trailers for delivery to peg marks. Imme-

Australian Journal of Telecommunications and the Digital Economy Volume 5 Number 1, March 2017
ISSN 2203-1693. Copyright © 2017 http://doi.org/10.7790/ajtde.v5n1.90

diately the laying out is proceeding satisfactorily, parties are put on to the work of arming the poles and fitting transposition plates. As far as practicable all fittings are placed on the pole whilst it is on the ground.

With the modern post-hole borer poles can usually be erected complete with arms and plates, thus effecting a saving in time. This type of borer lifts the pole as well as boring the pole hole, and has a long boom enabling it to grip the average pole well above its centre point, to allow for the shift of the centre of gravity towards the head due to the weight of the arms and plates. Another type of borer, which has no lifting mechanism, has been used on the Seymour-Bendigo route for boring stay holes. When used for poles it has been worked in conjunction with a winch truck fitted with sheer legs. One party follows behind the borer uprighting the poles and filling in and ramming. A separate party attends to the stays. One man follows the pole erecting party stencilling the poles. The work is so organised that the erected poles have been fitted with stays when required, and allowed to settle as long as possible prior to the commencement of wiring work.

Before wire is erected the section of route is checked to ensure that all poles are upright and stays are tight. Wires are erected and tensioned in $\frac{1}{2}$ to 1 mile sections, the weight method, described in the paper "New Method of Regulating Aerial Wires," by C. H. Hosking, in the June, 1951, issue of this Journal, being used for tensioning. Eight wires are strained at the one time. Where practicable, the wires are laid out in groups of four from wire reels mounted on a wire trailer or on the tray of a motor truck. A wire reel hav-

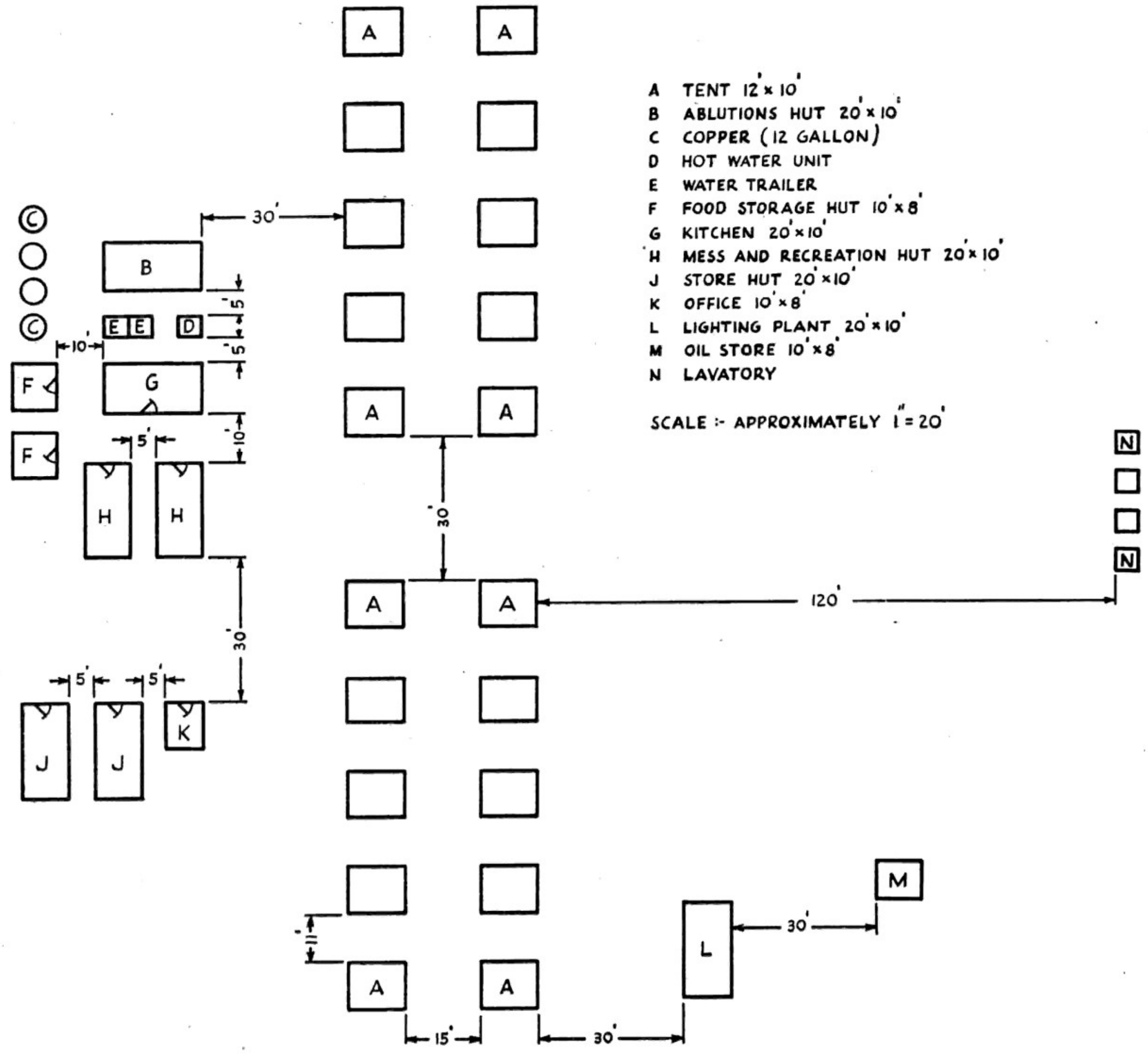

Fig. 9.—Large Line Camp—Layout.

Australian Journal of Telecommunications and the Digital Economy Volume 5 Number 1, March 2017
ISSN 2203-1693. Copyright © 2017 http://doi.org/10.7790/ajtde.v5n1.90

ing an automatic braking device has recently been developed and simplifies the work, provided care is exercised at angles in the route. In this type of reel, the wire running off in a straight line holds a spring-loaded brake off the rim of the wire reel by means of the tension in the wire. Should slack develop, the tension is released and the brake operates until the wire is again under tension. An equal number of wires are strained on each side of the pole in the one operation, in order to maintain an even pull on the pole and arms.

Camps for Large Construction Parties:

Many large trunk works are now carried out by camping parties because of the difficulty of obtaining suitable accommodation in towns near the work. Camps should be located as near as possible to the route, and so that the maximum distance of travel in any one direction is approximately 15 miles. A camp would then cover 30 miles of route. Other considerations, such as proximity to water and power, fuel supply and drainage will affect the final location of camps. Sleeping accommodation is provided by 10′ x 12′ tents with wooden flooring. The tent is fitted up for two men, and has two steel stretchers, mosquito nets where required, one table and two camp chairs. A large portable hut approximately 20′ x 10′ is provided for messing and recreation. The hut is furnished with tables and camp chairs, a heating stove and wireless.

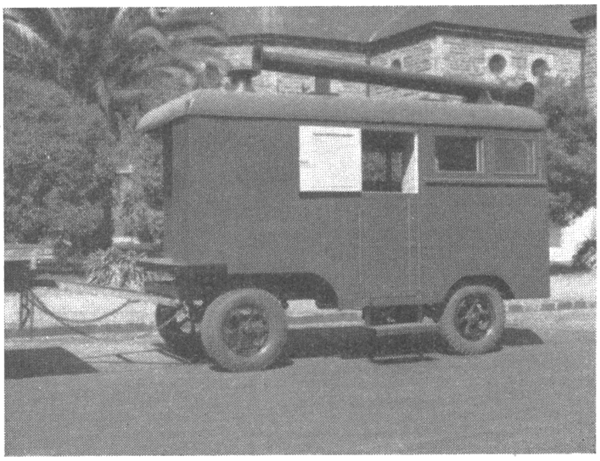

Fig. 10a.—Portable Kitchen—General View.

Kitchen arrangements consist of a trailer kitchen, and a small fly-proof hut to act as a pantry and to accommodate refrigerators. The kitchens are four-wheeled trailers with steel panelled bodies converted from surplus army "Wiles Cooker" vans. A wood fire or oil-burning stove is installed at one end, and the kitchen has both a solid and fly-wire door, a sliding panel in the roof, and fixed and sliding windows along the sides. All such openings are protected by fly-wire screens. Cupboards, shelves and drawers are fitted around three sides of the kitchen. The tops of the cupboards act as benches and also carry a stainless steel tank. A water tank is fitted between the stove and the sink. The oil-burning stove is the

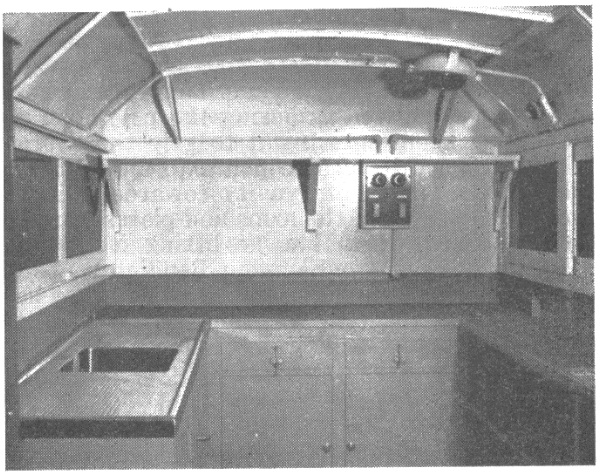

Fig. 10b.—Interior, showing steel sink, cupboards and bench, and electric light and power points.

type in which oil and water drip from separate tanks on to a hot plate, the preliminary heating of the plate being effected by allowing the oil to drip at a fast rate on to burning paper or wood chips. When the plate is heated, the oil rate is reduced and the water tap turned on. Oil and water taps are adjusted to give a clear, intense heat. The portable kitchen is a prefabricated wooden hut with similar fittings to the trailer kitchen. However, as it is not on wheels it is necessary to erect and dismantle it each time a camp is moved.

Lighting is normally provided by means of a 55 volt step down transformer where power is available. Where commercial power is not available eight six-volt car batteries are used, these being charged from a petrol generator set. Washing and bathing are catered for by means of a hot water service, wood or coke fired, and an ablutions hut, containing showers, baths and wash troughs.

Where a town water supply is not available the camp is pitched if possible near a river, and the water is pumped into a large water tank for distribution around the camp. Kitchen, ablutions hut and hot water service are grouped together to economise in piping, and for convenience. The mess hut is placed close to the kitchen. The camp office, a portable hut, is also included in this group. Beyond these buildings the tents are placed in rows, and beyond these again is the lavatory block. Earth drains are dug where necessary to dispose of surface water. Cleanliness is essential in a camp, particularly in hot weather, and all kitchen refuse is disposed of without delay. In some cases local farmers are prepared to cart away kitchen refuse, otherwise it is buried, use being made of the post-hole borer.

To reduce the number of flies present during the summer months, blow-fly traps are placed in suitable locations around the camp. Catering, re-

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creation and general camp matters are placed in the hands of a camp committee usually consisting of five members of the staff, including the Line Inspector and the cook. The Department provides the services of a cook for camps of ten or more men, with one or more assistants for camps of twenty men and over. Members of the camping party make their own arrangements regarding catering.

Fig. 10c.—Interior, showing oil stove and water storage tank.

A large camp of approximately forty men requires a regular staff of four, one to assist the Line Inspector on clerical duties and camp organisation, a cook, cook's assistant, and one on general duties around the camp. During weekends and on holidays a member of the camping party is rostered for a 24-hour period for camp protection duties. Such a camp covers an average area of half to one acre, and comprises twenty 12 feet x 10 feet tents, mess hut, trailer kitchen, store huts, ablution hut, hot water unit and portable lavatories. There are 94 distinct items of equipment, the total number of items being in the vicinity of 1400. A typical large camp layout is shown in Fig. 9 and three views of the portable kitchen are given in Figs. 10a, 10b, 10c.

Conclusion:

Trunk aerial construction using large parties has created a number of problems in organisation of staff, equipment and material to carry out the work speedily and without waste effort, and the experience gained on the Seymour-Bendigo route has been invaluable in meeting similar problems on other large works.

Australian Journal of Telecommunications and the Digital Economy Volume 5 Number 1, March 2017
ISSN 2203-1693. Copyright © 2017 http://doi.org/10.7790/ajtde.v5n1.90

A Trust-Aware RPL Routing Protocol to Detect Blackhole and Selective Forwarding Attacks

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Abstract: This research addresses blackhole and selective forwarding routing attacks, which are fundamental security attacks on the routing of data in IoT networks. Most IoT devices today, from medical devices to connected vehicles and even smart buildings, have the capability of communicating wirelessly with one another. Although, consumers are progressively embracing the concept of connected devices, recent studies indicate that security is not high on the priority list of manufacturers, especially in the way these IoT devices route and communicate data amongst themselves. Thus, it leaves the door wide open to attacks and compromises. In this study, a trust-based routing Protocol for Low-Power and Lossy Networks, addressing blackhole and selective forwarding attacks is proposed. We show that our proposed protocol is not only secure from blackhole and selective forwarding attacks, but also does not impose undue overheads on network traffic.

Keywords: IoT, RPL, Trust, Blackhole attacks, Selective Forwarding attacks

Introduction

The Internet of Things (IoT) can be described as a trend causing a global technological disruption today as a result of a melding of advances in computing and communication enterprises (Airehrour et al., 2016). IoT is set to transform, not only the user-to-machine interaction, but also the way machine-to-machine interacts. Already, we are witnessing the penetration of IoT devices in the market place. Various industrial sectors have begun witnessing the infiltration of IoT products into the fabric of several industries, including healthcare, energy, automotive and agriculture. Increasingly in these industries, users are witnessing the Industrial Internet of Things (IIoT), where devices such as sensors, exercise fit bits, robots and insulin pumps are progressively becoming more connected to one another (Chinn et al., 2014). It is perceived that Internet of Things will not only significantly change the future of the industrial sectors of the world but also will bring a positive transformation to how we live. A culmination of the full potential of the IoT vision will improve the standards of living of humanity because of the numerous value-creation opportunities while also improving

http://doi.org/10.18080/ajtde.v5n1.88

the careers of many (Ericsson, 2011). It is expected that the wide adoption of IoT will lead to a plethora of novel smart paradigms like smart healthcare, smart agriculture and smart power, amongst others. This could eventually evolve into new ecosystems of IoT that are propelled by self-aware, autonomous machines.

However, the fact that these devices can communicate with one another and over the web, poses a security risk to the Industrial Control Systems (ICSs) and other connected online devices, and hence requires better security mechanisms. There is no doubt that IoT is creating a new epoch of innovation that connects the digital and machine ecosystems and brings better speed and effectiveness to many sectors as recounted above. Nevertheless, with sensitive information increasingly being made available online via the deployment of IoT, and more endpoints exposed to attackers, the research community – and indeed the business world – are swiftly recognising that security in IoT networks and IoT generally cannot be an afterthought.

A study by McKinsey (Chinn et al., 2014) projects that the cost of cybersecurity will increase to $3 trillion by 2020 and of this, many of the security technology measures are futile. Further to the projection by Ericsson (Ericsson, 2011) that the number of connected devices will reach 50 billion by 2020, there is a pressing need to profoundly rethink security for the always-connected, high-volume and distributed world of the Internet of Things. One typical area of exposure in IoT is the routing packets between different IoT devices. These packets move across heterogeneous networks and are thus susceptible to various security attacks common to both the digital and machine world. At this stage of the nascent development of IoT, the security challenges need to be addressed to engender confidence in the public and globally achieve success with IoT.

The objective of this research is to develop a lightweight trust-based Routing Protocol for low power and Lossy networks (RPL) that will address blackhole and selective forwarding attacks in IoT. A blackhole attack is a denial-of-service (DoS) class of attack in which a malicious node drops data packets rather than forwarding them towards the expected destination. In a selective forwarding attack, a malicious node examines the packets received and then decides on the class of packets to drop. "Class of packets" indicates either data packets or route packets but not both. The intention, in both attacks, is to destabilise the network and the flow of data in the network (DoS).

The rest of the paper is organised as follows: a discussion on the IoT routing protocols and the current industry standards is presented; this is followed by an introduction of the security features available in RPL with a highlight on the challenges in its implementation. A trust-based mechanism for RPL routing protocol is further introduced as a mitigation strategy against the RPL attacks. We show that our proposed protocol is both secure from blackhole and selective forwarding attacks, while not imposing undue overheads on network traffic. We present our simulation results using the Contiki/Cooja environment and we demonstrate the efficacy of our proposed trust-based RPL routing protocol. Finally, we present our conclusions and final notes on our future work.

Internet of Things: A Routing Protocol Perspective

Routing Protocols in IoT

A routing protocol is a communication process tasked with the responsibility of making intelligent routing decisions during the forwarding of routing data among nodes. Routing in sensor networks could be classified into two types, namely: reactive routing system (where a sender node triggers a route discovery to transmit data packets to a destination node) and proactive routing system (where a node constantly searches for path information to a destination network, so that the path is ready before it is required). Protocols developed are based on any of these two systems (Kute et al., 2012).

Routing Protocols for Low Power and Lossy Networks

The Routing protocol for low power and lossy networks (RPL) is an IPv6 routing protocol designed by the Routing Over Low power and Lossy networks (ROLL) of the Internet Engineering Task Group Force (IETF) (Winter et al., 2012). RPL was designed as a standard for low power and lossy networks, which includes all IoT sensor nodes. RPL is a protocol based on proactive routing, which operates by discovering routes after the RPL protocol commences. It forms a tree-like topology known as Destination Oriented Directed Acyclic Graph (DODAG). Every node in the RPL network selects a preferred parent based on some metrics (hop-count, expected transmission count, link reliability and link colour object) and this preferred parent acts like a gateway for that node. If a node seeks to forward a packet for which it does not have a path in its routing table, it simply forwards it to its preferred parent, which has a path either to the destination or to its own parent for onward transmission until it gets to the final destination in the tree. Path selection is an important factor for RPL, and hence the protocol uses multiple metrics for this purpose. Every node in the DODAG computes its rank from the perspective of the position of the DODAG root node (sink) and in relation to the position of the other nodes. The rank of a node decreases in the upward direction towards the DODAG root while it increases from the DODAG root towards the leaf nodes (sender nodes). RPL operates in two modes to perform downward routing: RPL non-storing mode (source routing) and RPL storing mode (stateful in-network routing). In storing mode, each packet holds the route path to the destination. This entails the DODAG root maintaining details about each node within the network. It is important to note that when operating in a non-storing mode, forwarding RPL nodes in the network need to retain their in-network routing tables to identify where to send their packets. However, in both modes discussed above, the RPL DODAG root still retains a database of all nodes for downward routing purposes (Winter et al., 2012).

RPL utilises three control message types for the creation and maintenance of its graph topology and route table. The control messages include: DODAG Information Object (DIO), DODAG Advertisement Object (DAO) and DODAG Information Solicitations (DIS). DIO is used for creation, maintenance and discovery of the DODAG topology. When an RPL network is started, nodes exchange DODAG information via the DIO. The DIO helps nodes to select their preferred parents. RPL uses DAO messages to transmit the prefix of a node to its ancestor nodes for downward routing purposes. The DIS message is used by any unattached node in the network to solicit for a potential parent node. DIS is triggered by a node in a situation when it cannot obtain a DIO after a certain time interval (Winter et al., 2012). The creation of a RPL network in a DODAG is referred to as a RPL instance. While many RPL instances can consist within a DODAG, these RPL instances can have their own unique object functions (OF) for routing purposes.

Security in RPL

Security has been identified as being critical in sensor networks that are resource constrained (Le et al., 2012). In addition, the complexity of deployment and size is also a core concern for these resource-constrained networks, such that it may not be cost effective, if not practically unrealistic, to embed sophisticated security mechanisms in an implementation of a RPL system. Further to that, several RPL deployments can resort to link-layer security or other security systems to achieve their security goals while bypassing the security features that RPL may provide. Consequently, RPL security features could then be mere optional and non-obligatory extensions. RPL nodes can operate in three predefined security options.

The first is referred to as the "unsecured" option. In this option, the control messages in RPL are forwarded with no security primitives. The unsecured status implies that the RPL network could as well have adopted other security mechanisms (such as a link-layer security) to achieve application-specific requirements.

The second option is referred to as "pre-installed". In this option, nodes entering an RPL instance come embedded with pre-installed keys, which grants them processing and generation permission to safeguard RPL messages.

The third option is referred to as "authenticated". This option permits nodes to enter a network as leaf nodes using the embedded pre-installed keys while operating in a pre-installed mode, or nodes operate as multicasting nodes by getting a key from a central authentication authority.

In the last two options, there is a secure variant for every RPL message. The security features of 32-bit and 64-bit message authentication code (MAC) and encrypted message authentication code (ENC-MAC) options are well supported, while the algorithms (CCM and AES-128-bit encryption) have become new supported extensions in RPL as specified in the protocol messages (Winter et al., 2012). The safe variants of the RPL messages are meant to provide confidentiality, integrity, delay protection and replay protection as an added option.

However, the bad news is they all rely on past encryption solutions that have failed – and which continue to fail (Nordrum, 2016). Public Key Infrastructure (PKI) was developed about four decades ago to safeguard the communications between two human parties. It was at no time designed to handle the complications of managing industrial-scale networks of 50 billion devices that IoT promises to usher in. The very thought of having a central authentication authority for billions of devices makes it extremely awkward and inefficient.

Attacks in RPL

The RPL protocol, like any other wireless sensor network protocol, has been shown to be vulnerable to routing attacks. These attacks have been researched and covered in (Chugh et al., 2012; Tsao et al., 2014; Wallgren et al., 2013) among other papers; Table 1 shows a summary of attacks in RPL and some proposed solutions.

In (Weekly & Pister, 2012) the authors assume the use of cryptography and they specifically use the Secure Hash Algorithm 1 (SHA-1) as the hash function to protect the route messages being transmitted. The researchers also assume that the cryptographic system utilised is guaranteed hence, it will not be tampered with by any malicious nodes. As discussed under the section "Security in RPL", the use of cryptography (SHA-1) will certainly deplete the battery energy of the nodes and hence degrade network performance.

The assumption that the attacking nodes will not tamper with the cryptographic system makes the proposed solution impracticable in a real-world scenario. Of equal importance is the mobility of the nodes, when these nodes join and leave the network at will, implementing encryption becomes difficult as a specific node with certain network details required by other nodes suddenly becomes unavailable. The authors of (Raza et al., 2013) revealed the weaknesses in the implementation of the ContikiRPL viz-a-viz malicious attacks, and thus gave helpful insight into design issues that could help in the implementation of a better ContikiRPL. Raza et al. (2013) implemented an IDS system to defend against sinkhole and selective forwarding attacks and opined that it could also detect blackhole attacks; however, they assumed that key IDS nodes must be strategically placed. With a deluge of IoT devices randomly and remotely located, this may not be the case, and thus may not provide optimal defence against attacks.

Selective forwarding attacks work much like blackhole attacks; however in this type of attack, the malicious node selectively drops route or data packets so that it is almost imperceptible to the system that the loss was intentional. Most Selective attacks choose between dropping data packets or route packets. When a Selective forwarding attacker decides to drop only data packets, it does not intercept route packets. In this way, testing the end-to-end connectivity in a network will show no network problems, but packets still are not delivered to their destinations. Selective forwarding attacks have been discussed in several works and we present some references for further reading (Bysani & Turuk, 2011; Hu et al., 2014; Mathur et al., 2016; Ren et al., 2016).

A summary of various attacks and proposed solutions is presented in Table 1. In addition, Table 1 highlights the impact of the proposed solutions on network performance. In a later section, we present an algorithmic trust-based approach to secure the RPL routing protocol. This proposed protocol, when implemented in RPL, counters blackhole and selective forwarding attacks.

A Trust-Based Mechanism for RPL Protocol

Blackhole and selective forwarding attacks perform malicious activities like causing high packet drops and high route and control packet overhead, which depletes the limited resources of the IoT nodes. When malicious nodes propagate blackhole and selective forwarding attacks, network latency increases and the ranks of the nodes are altered, which causes a disruption to the RPL network topology and to its stability. Additionally, the rank alteration causes the nodes to re-compute their ranks. The rank alteration triggers a local repair – a self-healing mechanism that RPL uses to eliminate local routing loops. However, with the increase in these (blackhole and selective forwarding) attacks, the local repair eventually becomes inefficient, prompting a global repair by the DODAG root. A continuous initiation of these repair messages causes inefficiencies and disruption to the RPL network.

The section “Security in RPL” asserts that the security-related solutions to prevent malicious activities in RPL, which include cryptography and authentication operations, are unable to cope with the billions of IoT devices. Besides, the encryption technology could be considered complex and energy consuming in the context of the limited available resources of the IoT sensor nodes. Therefore, a trust-based mechanism which employs a lightweight solution with respect to the limited resources of the nodes, presents an interesting solution for the security of RPL routing.

Table 1 Summary of RPL Attacks and Countermeasures

Type of attack	Consequence on performance of network	Some proposed solutions
Rank	Minimal packet delivery and high packet loss; high-cost path selection and routing loop	IDS centred solutions (Raza et al., 2013), (Amin et al., 2009), VeRA (Dvir et al., 2011), TRAIL (Perreyet al., 2013)
Selective forwarding	Destabilisation of route topology	Heartbeat protocol (Wallgren et al., 2013)
Sinkhole	Transmitting network traffic via attacker node	IDS centred solutions (Raza et al., 2013), Parent fail-over, rank authentication technique (Weekly & Pister, 2012)
Hello flooding	Degrading of sensor energy	The initiation of RPL's local and global repair system addresses this attack
Wormhole	Destabilisation of route topology and network traffic	A Markle tree authentication solution system (Zhang et al., 2014)
Sybil and Clone ID	Route traffic truncation and node traffic isolation	Routing attacks and countermeasures in RPL-Based IoT (Wallgren et al., 2013)
Denial of Service	Unavailability of network resources	User centred IDS based system (Kasinathan et al., 2013)
Blackhole	High packet drop-rate and high control and route traffic overhead	SVELTE (Raza et al., 2013), A packet traffic counter monitoring system (Chugh et al., 2012), A parent system fail-over mechanism (Weekly & Pister, 2012),
Version number	High traffic latency and high control overhead with minimal packet delivery ratio.	VeRA (Dvir et al., 2011)
Local repair and Control overhead	Route and control traffic destabilisation	IDS system for intrusion detection (Le et al., 2012)
Neighbour attack	Falsification of route and network resource depletion	TRAIL (Perrey et al., 2013)
DIS attack	Network resource depletion	TRAIL (Perrey et al., 2013)

Embedding Trust in RPL

We describe below our proposed trust-based mechanism, which is embedded into RPL protocol. The aim of the mechanism is to compute a trust value for each node in the RPL network while embedding computed trust values for routing decisions. In this way, our proposed mechanism will deliver the combined values of providing an optimal routing decision while also isolating malicious nodes that may seek to drop control and route packets.

The trust mechanism also computes the effective feedback values between nodes. In our model, we make two basic assumptions:

i) that every node operates in promiscuous mode hence, they can overhear neighbour packet transmissions; and

ii) that every blackhole attacking node will over time begin to drop all route packets thus, the effective feedback communications between nodes (i.e. the number of packets a node could satisfactorily forward on behalf of the requesting node) will certainly reflect the blackhole nature of any node.

In our new protocol, a trust-based mechanism is embedded into RPL to enhance its capability to isolate blackhole attacks and selective forwarding.

When RPL is initially started, a comparison is made between nodes based on the expected transmission count and the rank of the nodes. These are normal RPL operations to determine preferred parents and routing decisions. Further to that, our computed trust values, as depicted in equation 1, are sorted in descending order of magnitude of trust. The corresponding trusted node(s) are selected for routing decisions while still maintaining the rank order of all nodes in the RPL network. The trust is computed as:

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

Where 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. Our trust-based algorithm is shown in Figure 1.

RPL uses routing metrics defined in its Objective Function to create the DODAG. Essentially, the routing metrics defined in the objective function help in the creation of the network routes and hence, resulting in an optimal route. In the Contiki implementation of RPL, there are two objective functions, namely: Minimum Rank with Hysteresis Objective Function (MRHOF) based on RFC 6719 (Gnawali, 2012) and Objective Function zero (OF0). Contiki uses MRHOF by default, which minimises the expected transmission count (ETX) values. This research work compares the MRHOF's implementation of RPL with our trust-based implementation of RPL.

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Algorithm for blackhole and selective forwarding attacks detection

```
Let N1 ← one available item in the NeighbourList[ ]
Let N2 ← another item next to N1 in the NeighbourList[ ]
   Compute      EP_{i,j} = 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 1 A trust-based algorithm for the isolation of malicious nodes in RPL

Simulation and Results

In the simulation, we have assumed that the IoT sensors are deployed in a smart building with one level. The InstantContiki 3.0 platform (Thingsquare, 2016) is used to perform the simulation. The various simulation parameters are listed in Table 2. During simulation, the system considers the interference from its surroundings, such as other devices or technologies that may be in use. We have also used the TMote Sky mote (Cooja simulator) for simulation and have defined the IEEE 802.15.4 broadcast range to be 50 metres and the interference range as 100 metres.

Table 2 Simulation parameters of a 30-node network

Simulation Parameters	
Simulation tool	Contiki/Cooja 3.0
Mote type	Tmote Sky
Simulation run time	3600 seconds
Simulation coverage area	70m x 70m
Interference range	100m
Total number of nodes	30
Root node (sink)	1
Blackhole attack nodes	3
Legitimate nodes	26
Deployment environment	Smart building
Wireless transmission range	50 metres
Network protocol	IP based
Routing protocol	RPL

Figure 2 shows the deployment of sensor nodes. The blackhole attacking nodes are coloured pink and were allowed to run as good behaving nodes for a while before being manually activated, after a certain time has elapsed, to act maliciously. The same topology was also used for the deployment and simulation of the selective forwarding attacks. As shown in Figure 2, nodes 28, 29 and 30 were used for blackhole and selective forwarding attacks during RPL operations. In the simulation study, we have assumed that the attack nodes behave as good nodes from the start and commence their malicious activities over time (when activated). Figure 3 shows the activation of the blackhole attacker node (node 28) after a set threshold timer while Figure 10 shows the activation of the selective forwarding attacker node (node 30). The set threshold timer is set to 5 seconds, by which time, the network is assumed to have converged based on the specifications of RPL routing operations.

Blackhole attacks

The section following presents the simulation results of the blackhole attacks' detection and the associated network performance measurements.

Detection and Isolation

In the simulation, sender nodes transmit packets to the sink node with the following stamp on each packet sent: time, source ID, packet type (sent or received), destination ID, sequence number and data size. This is shown in Figure 4. Packet sequence IDs are matched to ensure that packets sent are received by the sink node. Any sent packet sequence ID that is not matched with a corresponding received sequence ID by the sink node has either been black holed by the malicious node or affected by the lossy network link. However, the simulations showed strong reachability from the sender nodes to their neighbours. Furthermore, we have examined the packets dropped by the malicious nodes and they corresponded to the packets that have failed to reach the sink node. A complete log of the sent and received packets was analysed and the results presented in Figure 6. In Figure 5, the trust-based RPL protocol could detect and isolate the blackhole attacks during routing operations. A highlight of the attacks detected can be seen from the encircling blue pen-mark. In addition, Figure 5 displays a graph summary of attacks detected and isolated during RPL operation using the trust-based RPL protocol over a 60-minute simulation period at an interval of 5 minutes. As many as 600 attacks were detected between the 40th and 45th minute of the RPL operation. Conversely, in MRHOF's RPL implementation these attacks could not be detected, as there was no mechanism to detect nor isolate blackhole attacks.

It is of note that in RPL routing, a node rank change shows a re-alignment of a child-node to another preferred parent-node. Blackhole attack nodes advertise themselves to their neighbour nodes as better routes in a guise to attract these unsuspecting nodes while eventually dropping their packets. In Figure 7, a comparison of the frequency of node rank changes between the two routing protocols is made. RPL with MRHOF showed high frequency in rank changes reflecting its high level of susceptibility to blackhole attacks while our trust-based RPL protocol showed a very marginal level of susceptibility.

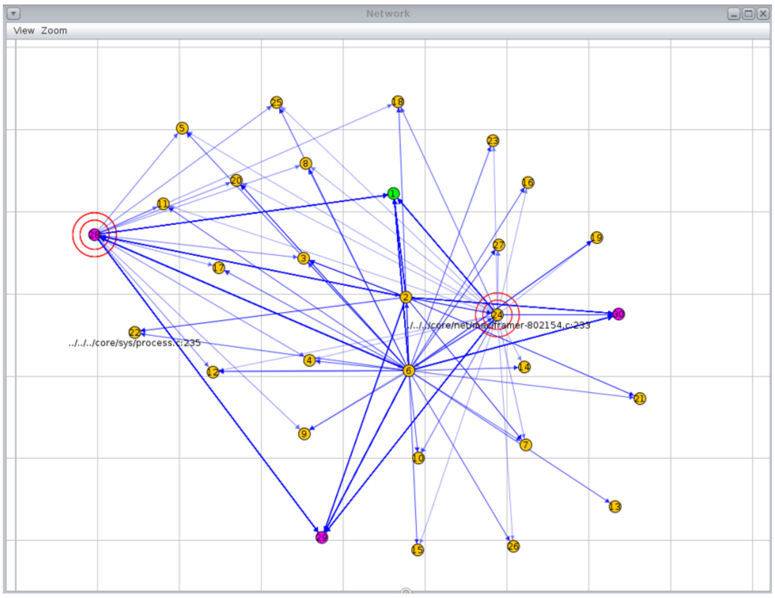

Figure 2 A network topology view of the IoT sensor nodes

Network Performance

Even though we have a protocol in place which could detect and isolate blackhole attacks during RPL operations, it becomes imperative that the new protocol should not impose undue overhead on the network performance. We present below a measurement of network throughput and packet loss rates to determine if our proposed protocol can deliver reasonable levels of network performance while isolating blackhole attacks when compared to MRHOF's RPL.

In Figure 8, the trust-based RPL showed significant improvement in throughput over the standard RPL (MRHOF). In fact, the throughput measurement of nodes 2-9, 15, 18, 19, 20, 22 and 25 was 0 kbps under MRHOF's RPL because of the blackhole attacks on the network.

This indicates that these nodes were child-nodes to a blackhole parent-node. Meanwhile, with the trust-based RPL protocol, none of the nodes had a throughput of 0 kbps, which implies that no child node had a blackhole parent node. This indicates that these nodes were child-nodes to a blackhole parent-node. Meanwhile, with the trust-based RPL protocol, none of the nodes had a throughput of 0 kbps which implies that no child node had a blackhole parent node.

Figure 9 displays a graphical representation of the percentage of packet losses in RPL routing operation under blackhole attacks. While the trust-based RPL protocol's packet loss stayed below 40%, the standard RPL (MRHOF) recorded a staggering 60 to 100% packet loss rate.

Thus, the two network performance measurements presented above justify the trust-based RPL routing protocol as a better performing protocol over the standard RPL (MRHOF) under blackhole attacks.

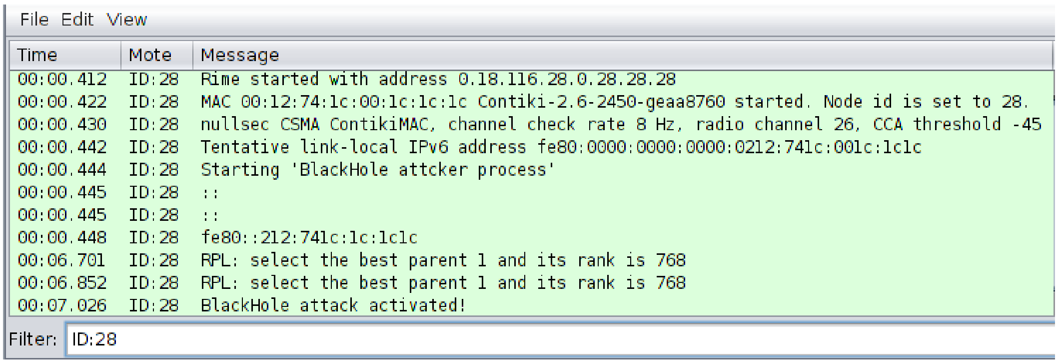

Figure 3 Blackhole attack activation in a RPL simulation network

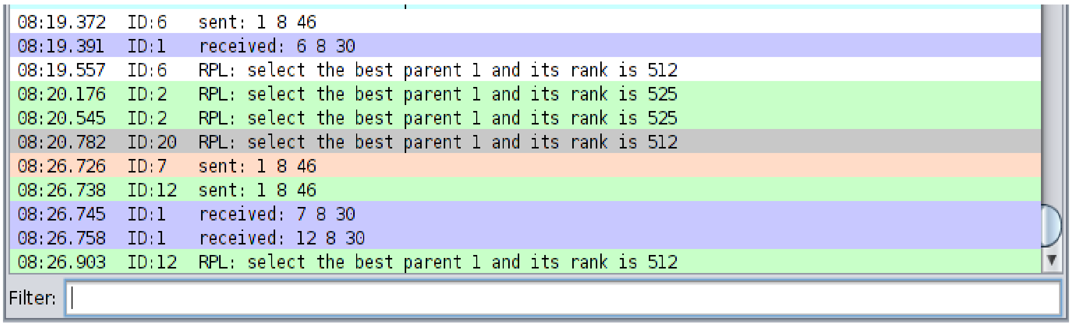

Figure 4 A sequence of packets sent and received by the sender and sink nodes

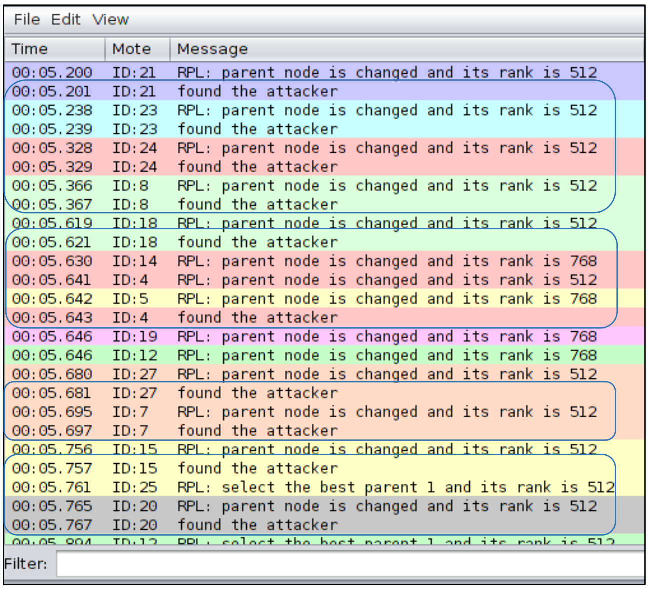

Figure 5 Detection of Blackhole attacking nodes during RPL operation

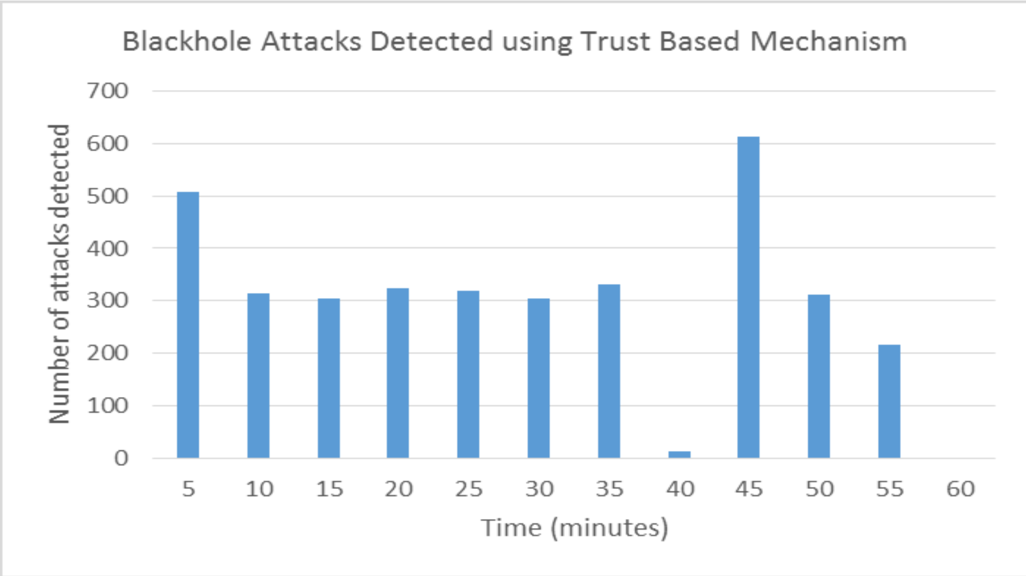

Figure 6 Trust-based detection and isolation of blackhole attacks in RPL

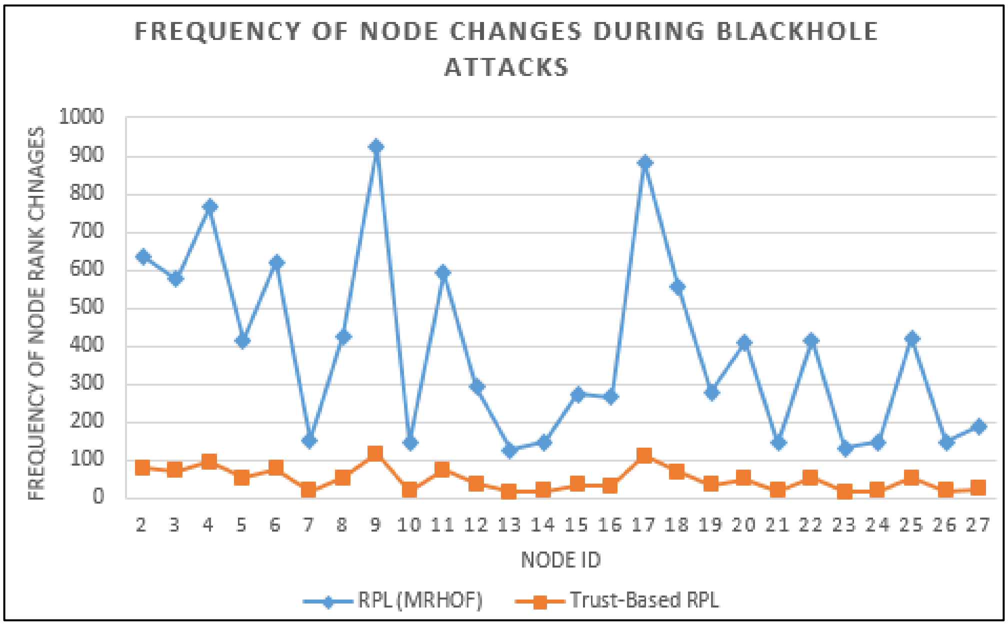

Figure 7 Comparison of frequency of node rank changes during blackhole attacks in RPL network during simulation

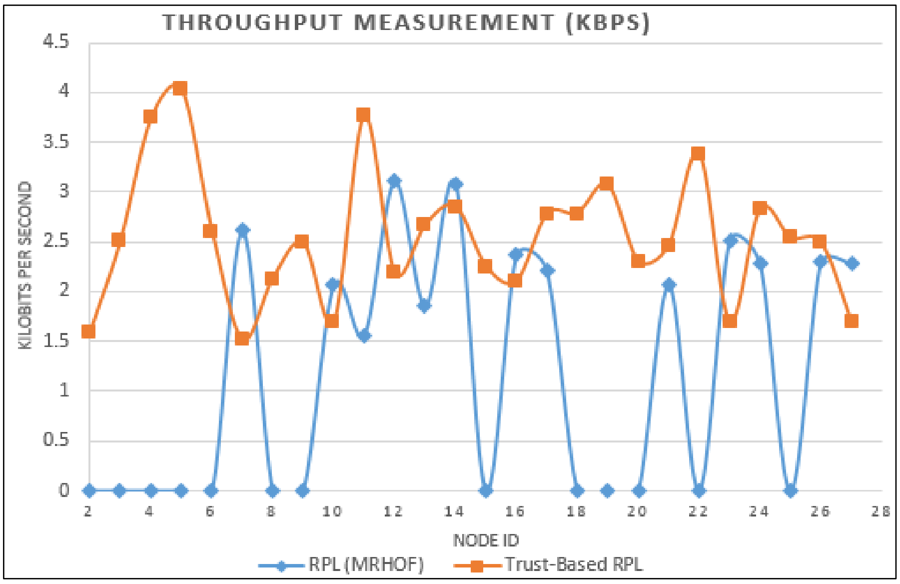

Figure 8 Comparison of throughput measurements between RPL (MRHOF) and Trust-based RPL

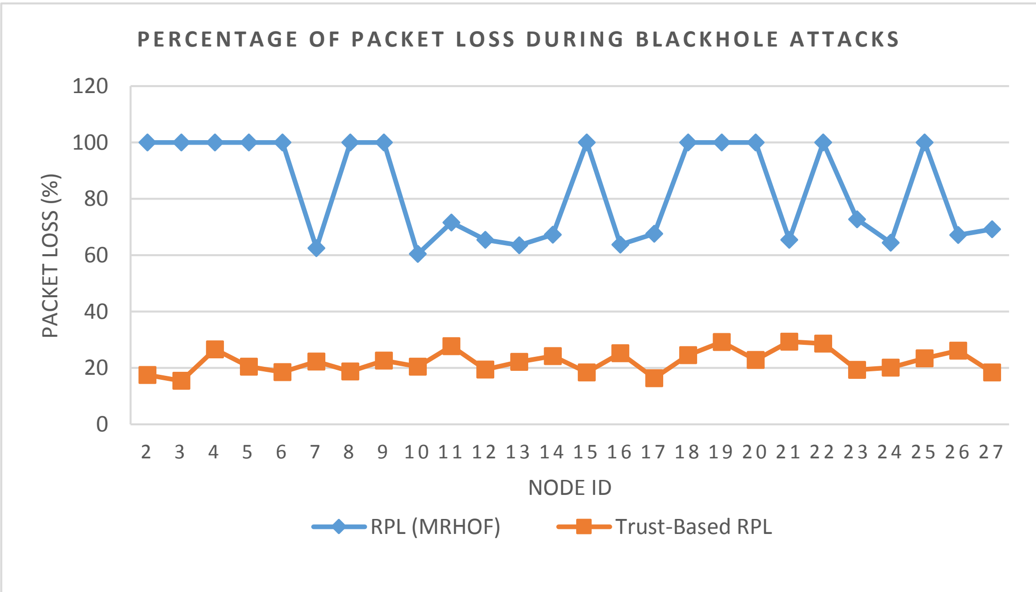

Figure 9 Packet loss rate comparison between RPL (MRHOF) and Trust-based RPL

Selective Forwarding Attacks

A summary of the simulation results of the selective forwarding attacks detection, isolation and network performance measurement are presented below.

Detection and Isolation

This section discusses the results of the simulation study of MRHOF-RPL and Trust-based RPL under selective forwarding attacks. As shown in Figure 10, node 30 was manually activated for selective forwarding attacks during RPL simulation. Similarly, other attack nodes

(28 and 29) were also activated. As explained in the sub-section under "Attacks in RPL", a selective forwarding attack is a subtle variation of a blackhole attack where malicious nodes selectively drop packets during routing communications. From the results shown in Figure 11, Trust-based RPL could detect and isolate selective forwarding attacks during routing operations. In the simulation, the first 25 minutes of RPL operation witnessed a flooding of selective forwarding attacks. However, starting from the 30th minute, the attacks were progressively and significantly reduced because Trust-Based RPL protocol could identify and isolate the malicious nodes. Hence, those malicious nodes were not subsequently considered for future routing decisions. On the other hand, MRHOF-RPL was not able to identify any of the selective forwarding attacks being perpetrated in the RPL network as evident from the high frequency of node rank changes shown in Figure 12. MRHOF-RPL showed significantly higher frequency node rank changes over our proposed trust-based RPL.

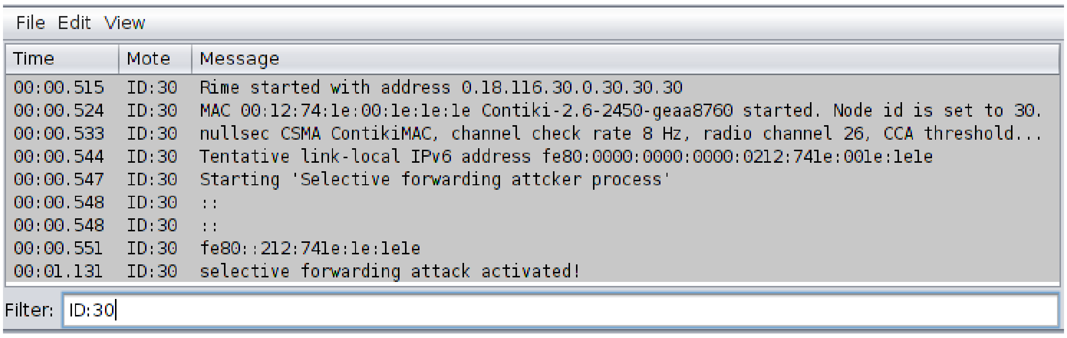

Figure 10: Activation of Selective Forwarding attacks in a RPL simulation network

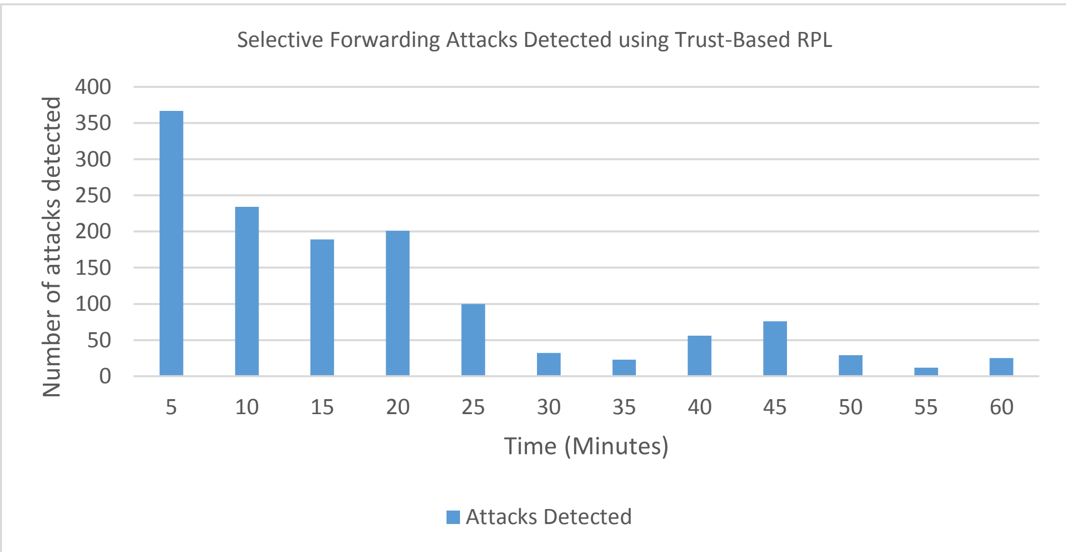

Figure 11: Detection and isolation of Selective Forwarding Attacks in a RPL simulation network

A RPL network with a stable topology will send route and control information based on the DIO trickle timer while the timer value increases with a stable network. However, an RPL

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network environment with high network topology changes will cause frequent transmission of control and route information. The topology changes could be due to the mobility of nodes or to suspicious activities of some malicious nodes in the network. This makes it necessary to have node re-alignment with new parents and that, in turn, results in a high frequency of rank changes among the nodes. Since the nodes are not mobile, we can conclude that changes in the rank of the nodes are purely because of the suspicious activities of the malicious nodes in the RPL network.

Figure 12 below provides a comparison of the frequency of changes in the node rank between the MRHOF-RPL and the Trust-based-RPL. MRHOF-RPL showed significantly higher node rank changes over our Trust-based RPL protocol reflecting a higher level of vulnerability to Rank attacks. As shown in the Figure, node 3 of the MRHOF-RPL had an initial spike of 800 node rank changes while that frequency in most other nodes ranges from 800 to 1,100. This range clearly reflects a high destabilisation of the network topology. As mentioned earlier in the paper, the high frequency of node rank changes not only destabilises the RPL network, but also affects both the efficiency and performance of any RPL network. Except for the spike experienced on node 6 with a node rank change of about 450 (refer to Figure 12), the Trust-based RPL protocol maintained a fairly consistent value of less than 400 node rank changes throughout the simulation time of 60 minutes.

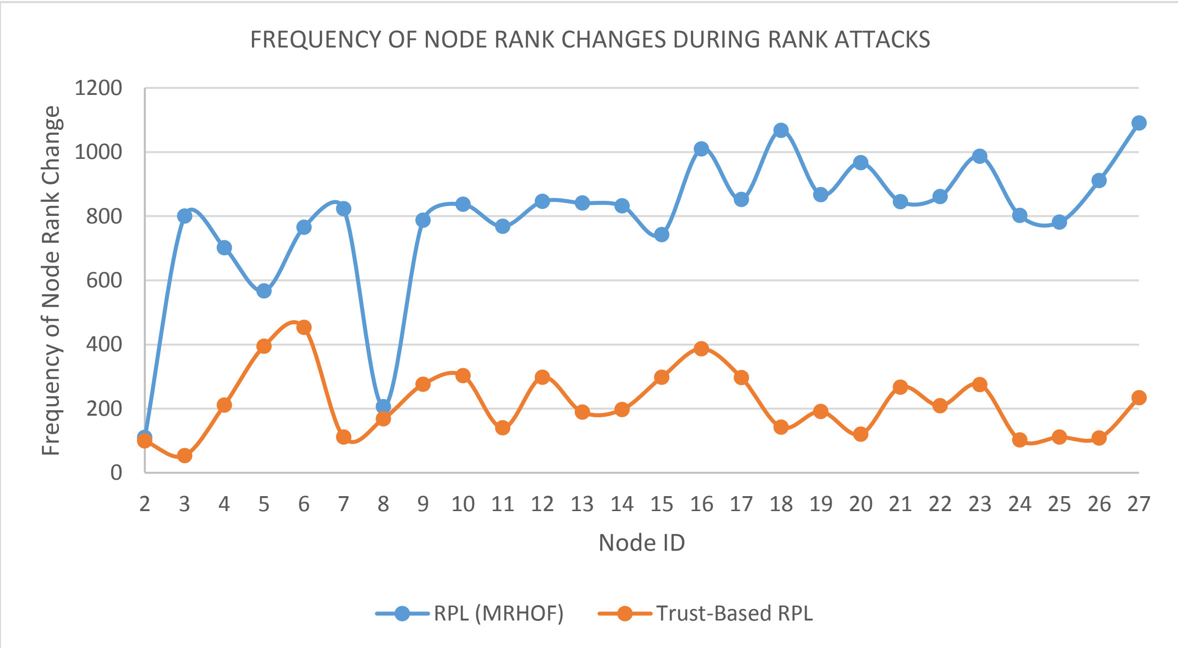

Figure 12: Comparison of frequency of node rank changes during Selective Forwarding attacks in RPL network simulation

Network Performance

Here we present a comparison of the MRHOF-RPL and the proposed Trust-based RPL during selective forwarding attacks based on network throughout and packet loss. As shown in Figure 13, in MRHOF-RPL, seven nodes, namely, 6, 15, 17, 19, 20, 22, and 26, have zero kbps throughput indicating that they are aligned to malicious parents that have selectively blackholed their packets. For example, following are the number of packets transmitted by each of these nodes that are not delivered to the sink node: Node 6 (packet sent, 52), Node 15 (packet sent, 52), Node 17 (packet sent, 52), Node 19 (packet sent, 52), Node 20 (packet sent, 52), Node 22 (packet sent, 52) and Node 26 (packet sent, 52). The remaining nodes, although they had some packets delivered to the sink node however, by observing their disproportionate packet delivery rates, we can conclude that they were affected by the activities of the malicious nodes in the network.

On the contrary, Trust-based-RPL has shown significant improvement in throughput over MRHOF-RPL and has maintained a much higher throughput range overall, except for nodes 2 and 23 that record less than 2 kbps in throughput due to malicious activities. Thus, we can conclude that, as evident from Figure 13, our Trust-based RPL protocol provides much better network throughput than the MRHOF-RPL protocol during selective forwarding attacks.

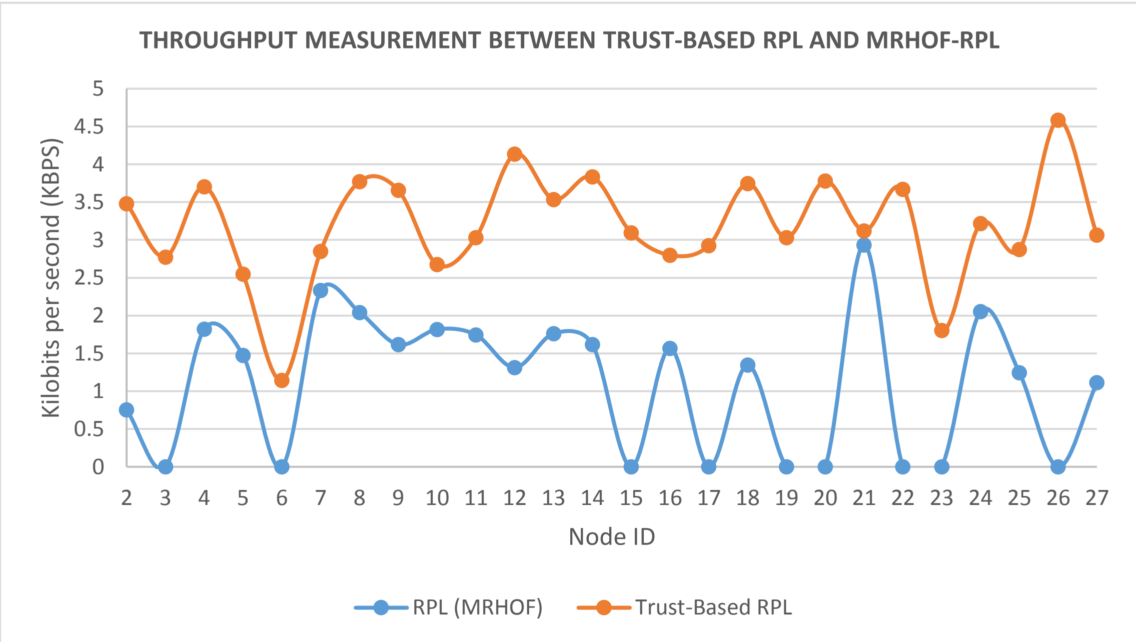

Figure 13: Comparison of network throughput between Trust-based-RPL and MRHOF-RPL during Selective Forwarding attacks

Figure 14 presents a comparison of the two protocols with regards to the percentage of packet losses in each node. From the Figure, it is evident that under selective forward attacks, while MRHOF-RPL had 60-70% lost packets during RPL operation, in the case of Trust-based RPL it was only 30%. This proves the efficacy of our Trust-based RPL protocol in delivering an acceptable network performance while isolating selective forwarding attack nodes in the network.

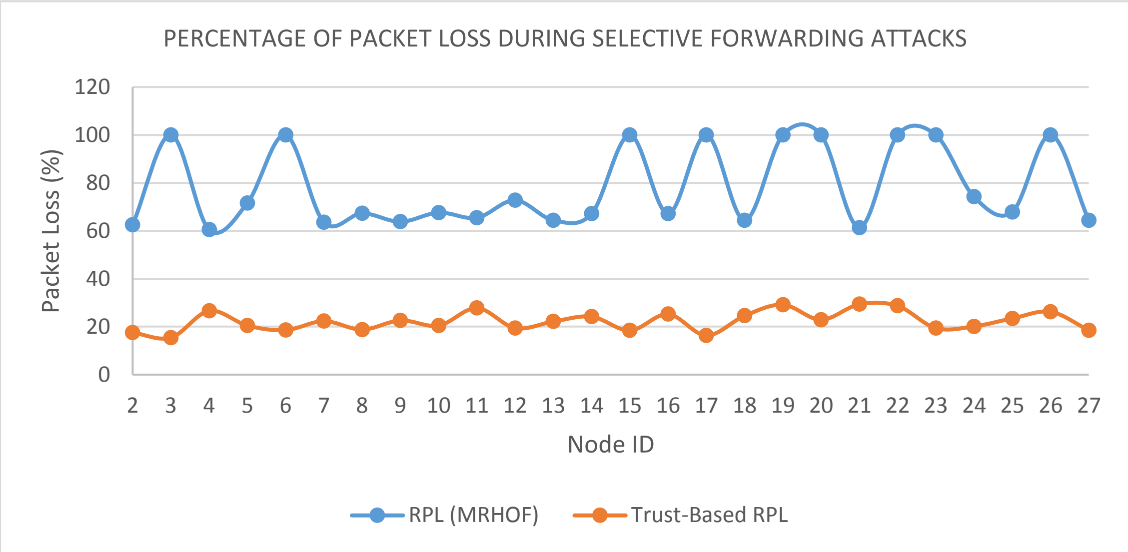

Figure 14 Percentage of packet loss in Trust-based-RPL and MRHOF-RPL protocols during selective forwarding attacks

Conclusions

In IoT networks, compromised sensor nodes can destabilise the integrity of data routing by intentionally (a) transmitting incorrect control and route information, (b) dropping all packets, (c) injecting false routing information during data aggregation, and (d) hampering the forwarding of composite data. Since cryptographic methods have proved to be inadequate in the prevention of these attacks, especially on a massive scale of billions of IoT nodes, a trust-based RPL protocol has been presented in this paper. The proposed novel reliable routing protocol provides a feedback-back based trust-aware security protocol for IoT networks. The protocol computes a trust value for any node in the IoT network based on the good packet forwarding behaviour of neighbouring network nodes. The trust value is dependent on the positive feedbacks observed about the packet forwarding behaviour among nodes. From results presented in the simulation, we therefore conclude that our proposed trust-based RPL protocol can provide comprehensive security against blackhole and selective forwarding attacks.

Our future work intends to incorporate energy metrics into the protocol to isolate the nodes with depleting energy levels from routing decisions, while providing them with the opportunity to recoup their battery power.

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Review of the Mexican Telecommunications Market

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Abstract: Historically in Mexico, as in many other countries, the development of the telecommunications sector has been characterised by the presence of a single operator owned by the State, followed by a privatisation process. However, in the years that followed, a number of obstacles to competition and the development of telecommunications were identified. As a result, a constitutional reform was implemented in 2013. It consisted of a series of measures that have contributed to shape the sector as it is nowadays, with favourable outcomes that have begun to be tangible. This article recounts the evolution and current state of the Mexican telecommunications ecosystem, briefly describing new challenges and opportunities posed by the digital economy.

Keywords: Mexico; Telecommunications; Constitutional Reform; Competition; Policy and Regulation.

Introduction: overview of the current situation

In recent years the telecommunications sector in Mexico has been characterised by a transition toward conditions of effective competition, mainly due to recent measures taken by the authorities. That is, as a result of the acknowledgement of the importance of this sector, efforts had been made for more than a decade in order to foster competition, infrastructure development and favourable outcomes for consumers. Examples included number portability rules which were implemented in 2008, although back then they did not include key aspects such as the obligation to carry out the process within a 24 hour time frame (IFT, 2015); and the requirement to use open network architecture design to promote competition through interconnection and interoperability (Cámara de Diputados del H. Congreso de la Unión, 2014).

However, these efforts proved insufficient in an environment where América Móvil (traditionally known as Telmex in the fixed market and Telcel in the mobile market), stood out for its market power and the difficulty faced by other companies to compete with it in fixed and mobile services. (It is worth mentioning here that the broadcasting sector has also been characterised by the dominance of Televisa, a broadcaster and media content company that has sustained a high market share for many years). For this reason, a constitutional reform in telecommunications and broadcasting took place in 2013. This reform was based on the identification of a number of factors hampering the development of the sector, as well as the analysis of international best practices as a solution to those problems.

This assessment was contained in a document by the Organization of Economic Cooperation and Development (OECD), whose citation will be based on the organisation's acronym in Spanish: OCDE (2012). Following the assessment, the President sent a proposal to the Legislative Power to reform a series of constitutional articles on telecommunications. The proposal encompassed the following objectives from the "Pact for Mexico", an agreement between the country's Executive Power and the main political parties: establishing broadband access as a human right, reinforcing the autonomy of the regulatory agency, developing both a backbone and a wireless wholesale network, developing a digital strategy and creating specialised courts on economic competition and telecommunications (Hernández & Navarro, 2016).

Along with the reforms to the Constitution, the Federal Telecommunications and Broadcasting Law (*Ley Federal de Telecomunicaciones y Radiodifusión,* July 2014, henceforth LFTR) and other related laws, the autonomy of the regulatory agency for the telecommunications and broadcasting sectors was reinforced. In this case, the word "reinforced" refers to the fact that although there was already a separate governmental agency responsible for supervising the development of the referred sectors, its operating budget and its major regulatory decisions depended on the central government and/or the Ministry of Communications and Transport (*Secretaría de Comunicaciones y Transportes*). This was part of a problem that is commonly referred to as "double window" (Hernández & Navarro, 2016). With this in mind, and as part of the key problems facing the sector, it was considered that the regulator needed autonomy as well as a series of specific powers and responsibilities.

Therefore, ever since the constitutional reform of 2013 was implemented, the relevant regulatory framework has established that the Federal Telecommunications Institute (*Instituto Federal de Telecomunicaciones*, IFT) is the independent and autonomous regulator for the telecommunications and broadcasting sectors (Table 1 presents a relation of the main companies of the telecommunications sector that are subject to IFT's authority, and the markets in which they operate). It has its own operating budget and constitutional warrants to avoid any external (private or governmental) influence on its decisions. Its charter consists of regulating and promoting competition and the efficient development of both telecommunications and broadcasting. For this purpose it is in charge of regulating, promoting and supervising the efficient use of radio spectrum, orbital resources, satellite services, public telecommunication networks and access to passive and active infrastructure and to other essential inputs.

Table 1 Main telecommunications operators in Mexico.

Market	Operator	Network Technology
Mobile (Voice & Broadband)	AT&T and Unefon	GSM/iDEN (2G)
		CDMA 1xEV-DO/ W-CDMA(3G)
		LTE (4G)
	Telefónica (Movistar)	GSM (2G)
		W-CDMA(3G)
		LTE (4G)
	América Móvil (Telcel)	GSM (2G)
		W-CDMA(3G)
		LTE (4G)
	Virgin Mobile	Mobile Virtual Network Operators (MVNOs)*
	Qbo Cel	
	Maz Tiempo	
	Weex	
	Maxcom	
	Cierto	
Fixed (Voice)	Axtel-Avantel-Alestra	Fixed Wireless
	Megacable-MCM	VoIP
	Maxcom	Fixed Wireless
	GTM	Fixed Wireless
	Televisa	VoIP
	Total Play	VoIP
	América Móvil (Telmex)	PSTN
Fixed (Broadband)	Megacable-MCM	Cable Modem
	Maxcom	xDSL
	Axtel-Avantel-Alestra	FTTx/WiMAX
	Televisa	Cable Modem/FTTx
	Total Play	Cable Modem/FTTx
	América Móvil (Telmex)	xDSL/FTTx

Source: Own elaboration with data from IFT (2016a) and Ovum TMT Intelligence Informa (2017).
* These are the MVNOs for which the IFT is currently reporting data on number of subscribers, although the list is not limited to them. A more exhaustive list should include other MVNOs, such as Teligentia, Quickly Phone, Pepephone, Flashmobile, Tuenti, etc.

The IFT is also the competition and antitrust authority in the sectors it regulates, exerting exclusive powers in the terms established by the corresponding legal framework (Article 7, LFTR) and being able to establish specific regulation and sanctions with full autonomy. These powers and responsibilities consist of guaranteeing free competition, by investigating and implementing measures to deal with market power, monopolistic practices, mergers and other situations that may work against the achievement of efficient market outcomes. It is important to note that these powers were vested on the IFT after the 2013 constitutional reform, for traditionally they had been exercised by the Federal Competition Commission (*Comisión Federal de Competencia*). The latter continues to oversee the development of competition for the other sectors of the economy, functioning as an independent regulator as well.

Among the aspects that are deemed essential for the development of the telecommunications and broadcasting sectors is consumer protection. A list of consumer rights, and mechanisms to ensure their protection, is included in the 191st article of the LFTR. Besides these and other specific aspects related to consumer protection that can be found in this legislation, provisions for consumer protection are based mainly on the Federal Consumer Protection Law (*Ley Federal de Protección al Consumidor,* LFPC). This means that there is convergence in the subject, both in terms of legal instruments and regulatory institutions. Specifically, within the scope of the LFPC, the IFT protects consumers' rights and so does *Procuraduría Federal del Consumidor* (PROFECO), which is an independent governmental agency. For example, the rights contained in the 191st article of the LFTR are to be enforced by PROFECO which, according to the 21st transitory article of the LFTR, has to create a specialised department in charge of these functions. Moreover, PROFECO is designated to be in charge of addressing complaints by the users. It is also noteworthy that for the broadcasting sector, operators are obliged to have an advocate for their audiences, which has to address complaints and suggestions by the audiences, on contents and programs.

The constant evolution of the sector and the transition to a digital economy has brought about a debate regarding the regulation of an increasing number of technological scenarios, business models and new markets, especially transversal (i.e. multi-market) possibilities. In this sense, the Mexican case is not different from other regions where the same debate is currently happening. Even though the 2013 constitutional reform devoted significant efforts to implementing ex-ante regulation that was considered necessary, the Mexican regulator is still faced with the challenge of continuing to define its scope in market application and to devote significant efforts to find a regulatory balance for the aforementioned new possibilities. In other words, the Mexican regulator is aware of the difficulties entailed by the definition of new markets subject to specific regulation, as well as the transversal nature of such markets (i.e. that involve more than one market, regulatory instruments and/or competent authorities), and the possibility of relaxing certain regulatory provisions for "traditional operators" in order to allow for a level playing field.

An example of the challenges posed by the emergence of new services is the obligation for over-the-top, video-on-demand services to include minimum amounts of local content (currently over-the-top services are not regulated by the IFT). An example of transversal possibilities is privacy and personal data protection (in Mexico there are provisions on this subject in either

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the LFTR or the Federal Law on Protection of Personal Data Held by Private Parties, *Ley Federal de Protección de Datos Personales en Posesión de los Particulares*). As for the relaxation of rules for traditional operators, an example is the possibility of allowing traditional broadcasters more flexibility in the ways in which they present advertisements.

An important concept that is already contemplated in the LFTR is net neutrality (article 145); however, this is still subject to the publication of specific guidelines, for aspects such as quality of service and infrastructure development. For other potential scenarios, the current legislation has left room for self-regulatory schemes, mainly for popular applications/content providers. For example, regardless of specific provisions that are or could be found in national regulatory frameworks, various popular applications/content providers already adhere to international standard rules regarding the use of personal data. In Mexico, this situation will likely change, within an environment of constant innovation that will also keep raising concerns in terms of investment incentives for Internet service providers (Boliek, 2009; Courcoubetis et al, 2014; Cheng et al, 2011; Choi & Kim, 2008; Krämer & Wiewiorra, 2009; Njoroge et al, 2010).

Historical evolution of the telecommunications market in Mexico

An overview of the telecommunications market through the last 40 years starts with fixed services, which were provided by Telmex, a monopoly that was owned by the government since 1972. By the end of that decade the number of fixed lines had trebled. In spite of this, during the 80s the development of the company and the telecommunications market was affected by a macroeconomic and external debt crisis and a devastating earthquake, and the growth in the number of lines dropped to 7%. The economic and financial situation also affected the quality and reliability of telephone services. Given that the government considered Telmex as a cash cow of revenue for other sectors of the economy, and for serving Mexico's external debt obligations, Telmex was not able to make its necessary network investments, and started to operate with obsolete technologies (Del-Villar-Alrich, 2006).

In 1990 Telmex was sold to the private sector. As part of this privatisation, the government granted it a licence that is set to expire in 2026. This licence enables the company to provide voice, data, text, audio and video transmission services. Telmex was also granted a monopoly of domestic and international long-distance call service until 1997. The company was required to increase the number of basic service lines at a minimum average annual rate of 12% in the period from 1990 to 1994. In addition, the licence included provisions in terms of the accounting separation of local and long-distance calls (international and national) in fixed networks; the prohibition of monopolistic practices; the obligation to reduce waiting times for repairs and installations; the improvement of the quality of service and the extension of coverage in rural areas (with a target of at least one telephone service in each village of 500 inhabitants or more, by 1994); automatic switching services for all communities with more than 5,000 inhabitants; and 2 public telephones per 1,000 people (increasing to 5 per 1,000 people by 1998) (Robles-Rovalo et al, 2006). Telmex was also obliged to provide its regulators with four-year work plans, and was subject to specific price regulation based on a cap-price system applied to the weighted average of a basket of regulated services.

1990 was also the year in which the mobile phone service started in Mexico. This market was the main driver of the later development of the telecommunications industry, growing at a composite rate of 40% in the period 1996-2009. Since in 1996 Mexico lagged behind other OECD countries in the development of the mobile telephony market, its high growth reflected a process of recovery from a low penetration rate (Kuhlmann et al, 2010). Nevertheless, Telmex was also present in this market with its subsidiary Telcel, founded in 1989, and has been the largest company in this sector in Mexico (nowadays both Telcel and Telmex are part of América Móvil), sustaining a market share of more than 50% for several years (OCDE, 2012). This concentration level had been accompanied by prices that were high in comparison to other countries (Del-Villar-Alrich, 2006), even though they have been decreasing in recent years (INEGI, 2017).

Another key aspect in terms of competition was interconnection. In regard to the long-distance telephone service, interconnection rates had reduced between 1997 and 2006. However, the country had been lagging in terms of the obligation of Telmex to provide interconnection in all the facilities with routing capacity, which was technically feasible since the year 2000 (Del-Villar-Alrich, 2006). In fact, access to the incumbent's infrastructure was clearly identified as an obstacle to competition, both in mobile and fixed markets. In this sense, the OECD identified a series of areas of opportunity such as wholesale services, in which it recommended that companies with market power should make service level agreements available to new entrants, with appropriate indicators of access to leased lines and other network elements.

The OECD also suggested that there was room for improvement in terms of overcoming existing barriers to obtaining rights of way. It sustained that the regulator needed to be competent to declare bottlenecks and essential infrastructures, enabling access to these under non-discriminatory conditions, including unbundling the incumbent's local loop and co-location with cost-oriented prices (OCDE, 2012). These issues represented obstacles to the development of greater competition in broadband access. In addition, cable TV operators were not allowed to provide broadband services until 2003 (Del-Villar-Alrich, 2006). Moreover, it was not until 2006 that there was a convergence agreement whereby telecommunications operators were allowed to offer pay TV services and broadcasters were allowed to offer telecommunications services (SCT, 2006). Nevertheless, the concessions system involved costly requirements, which served as barriers to entry, prevented operators from accessing other markets in the sector and limited the use of new technologies (e.g. voice over IP), which translated into consumer losses (Mariscal & Rivera, 2007).

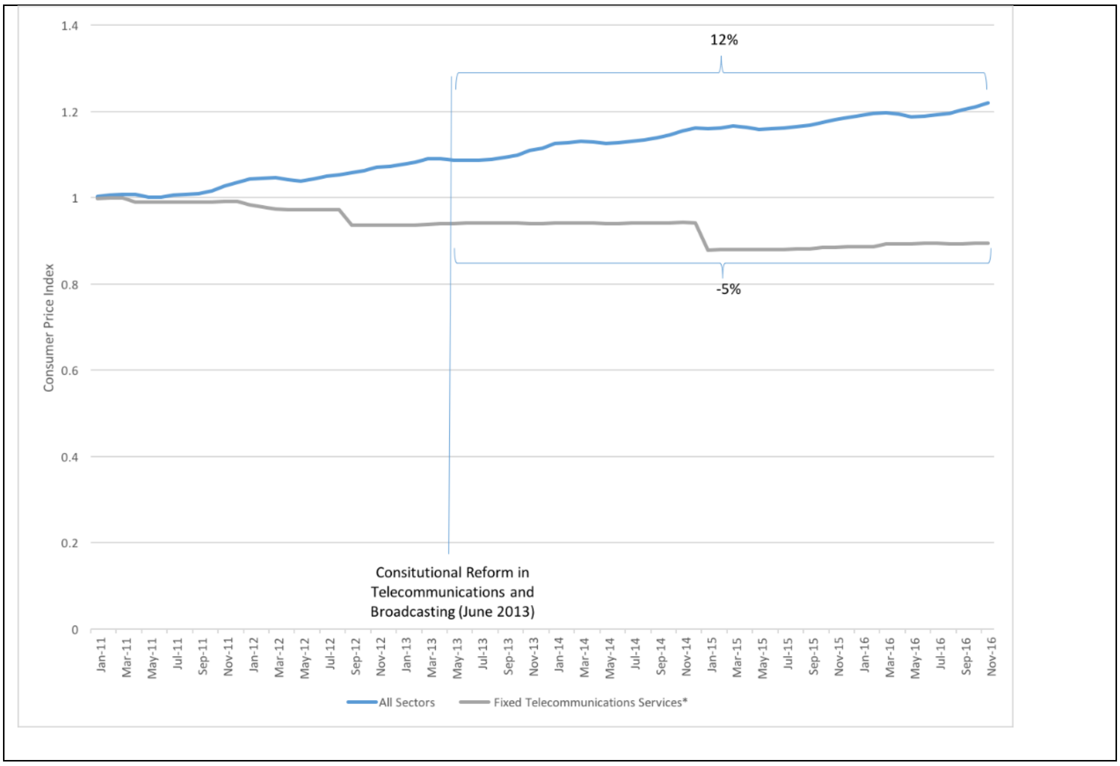
Regarding mobile-to-mobile interconnection rates, their evolution since the calling-party-pay scheme was implemented in 1999 had been slow, as they started at 0.19 Mexican pesos and were still 0.14 Mexican pesos in 2006. Also in the mobile market, one of the main issues was related to radio spectrum and its availability (Mariscal & Rivera, 2007). Allocations of this essential resource were concentrated among very few players (Robles-Rovalo, 2016) and a concern was that operators who held spectrum rights could hoard them and prevent third parties from obtaining them to offer their services (Robles-Rovalo, 2016). Another area of opportunity, related to infrastructure access, was the entrance into the market of MVNOs. In addition to these issues, the existence of restrictions to foreign direct investment was identified as an obstacle in the development of the sector (OCDE, 2012).

Current situation of the market

Competition and consumer benefits

In describing the current status of the market, it is important to start by pointing out that at the core of the LFTR (Article 2) is the objective of establishing conditions of effective competition in the provision of telecommunications and broadcasting services. Competition is seen as a desirable goal because of the benefits it can bring to a market and its users, deriving from the pressure competition places on firms to be efficient, innovative and customer focused in order to thrive and survive. These benefits include lower prices, higher productivity, more service choices, and greater connectivity (The World Bank, InfoDev and the International Telecommunication Union, 2011).

As noted in the previous section, price levels for voice services were one of the concerns behind the reform, and with the various measures aimed at enhancing competition prices have continued to decrease. This can be seen on Figure 1 (a and b), which shows the evolution of Consumer Price Indexes (CPIs) for fixed and mobile services, and how they decreased, whereas the CPI for the entire economy exhibited the opposite behaviour. Even so, prices had already been decreasing but a key concern was that they were higher than in other countries. Figure 2 (a and b) shows how this situation has changed, now that Mexico is in the upper third on the list of OECD countries in terms of lowest mobile voice prices.

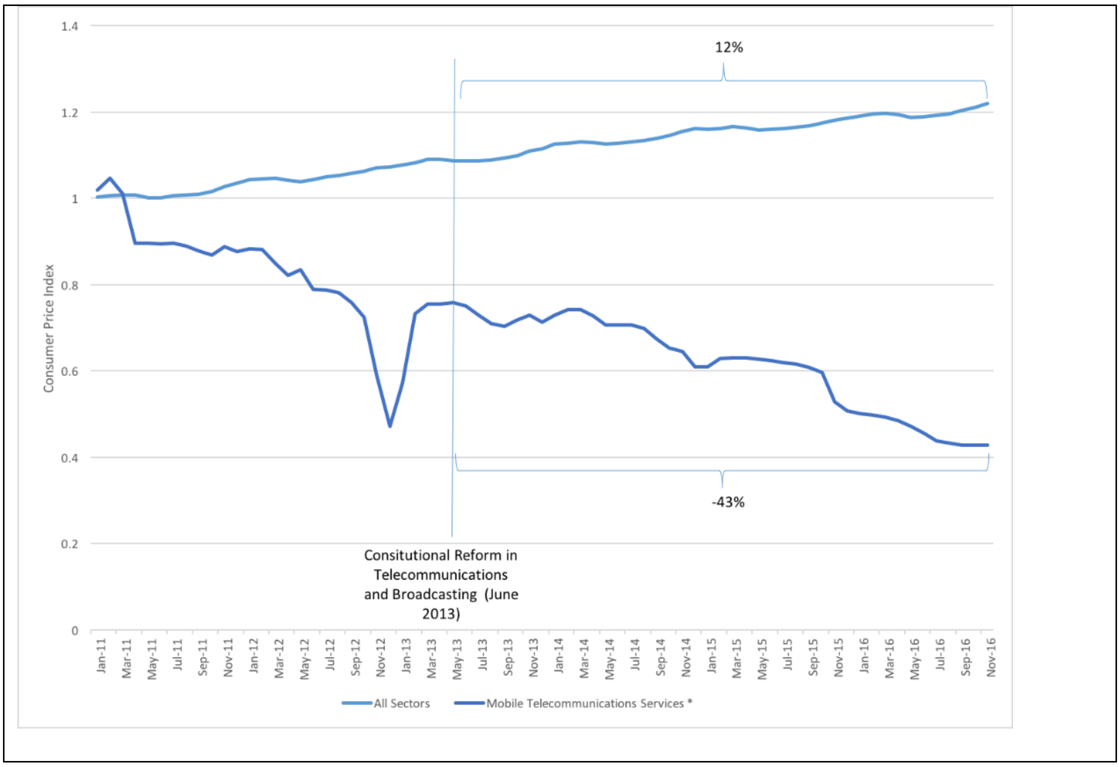


*The definition of mobile telecommunication services is based on the North American Industrial Classification System (NAICS).

"All sectors" comprises primary, secondary and tertiary activities, according to NAICS.

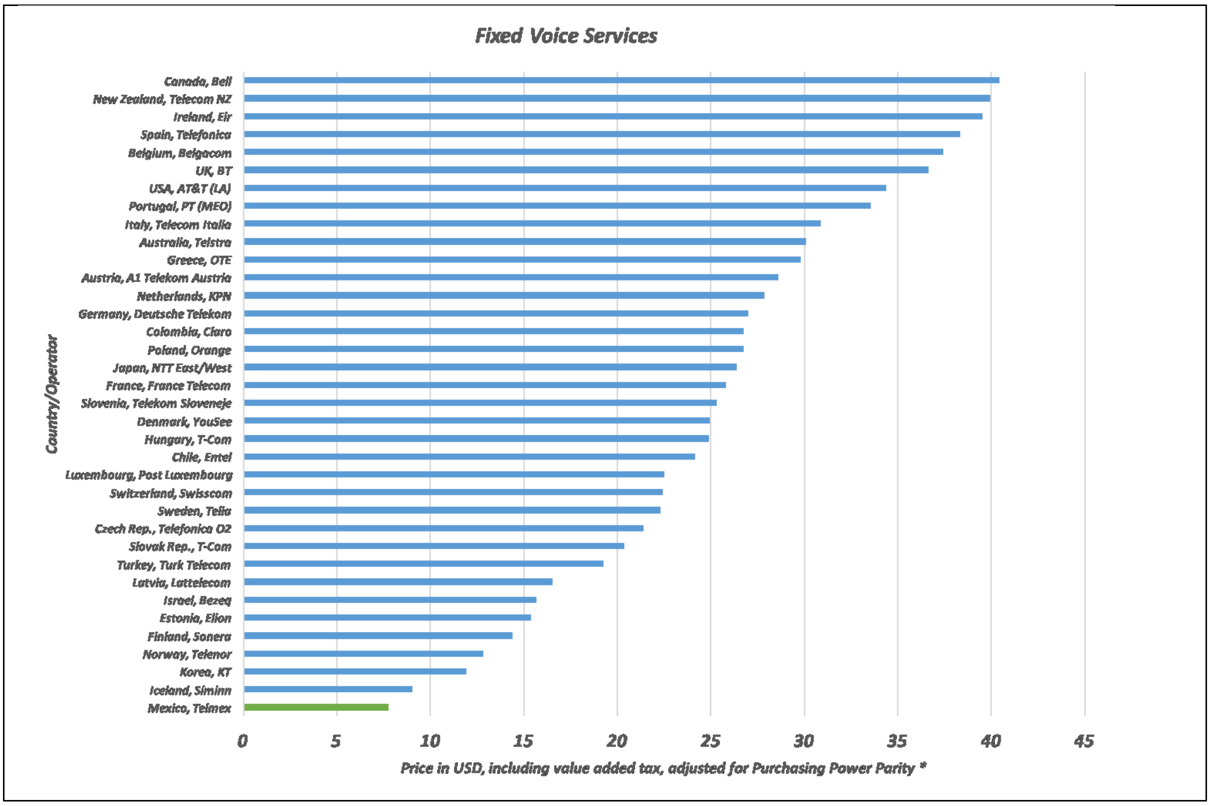
Source: INEGI (2016).

Figure 1a Evolution in fixed telecommunications CPIs in Mexico. 2011-2016.



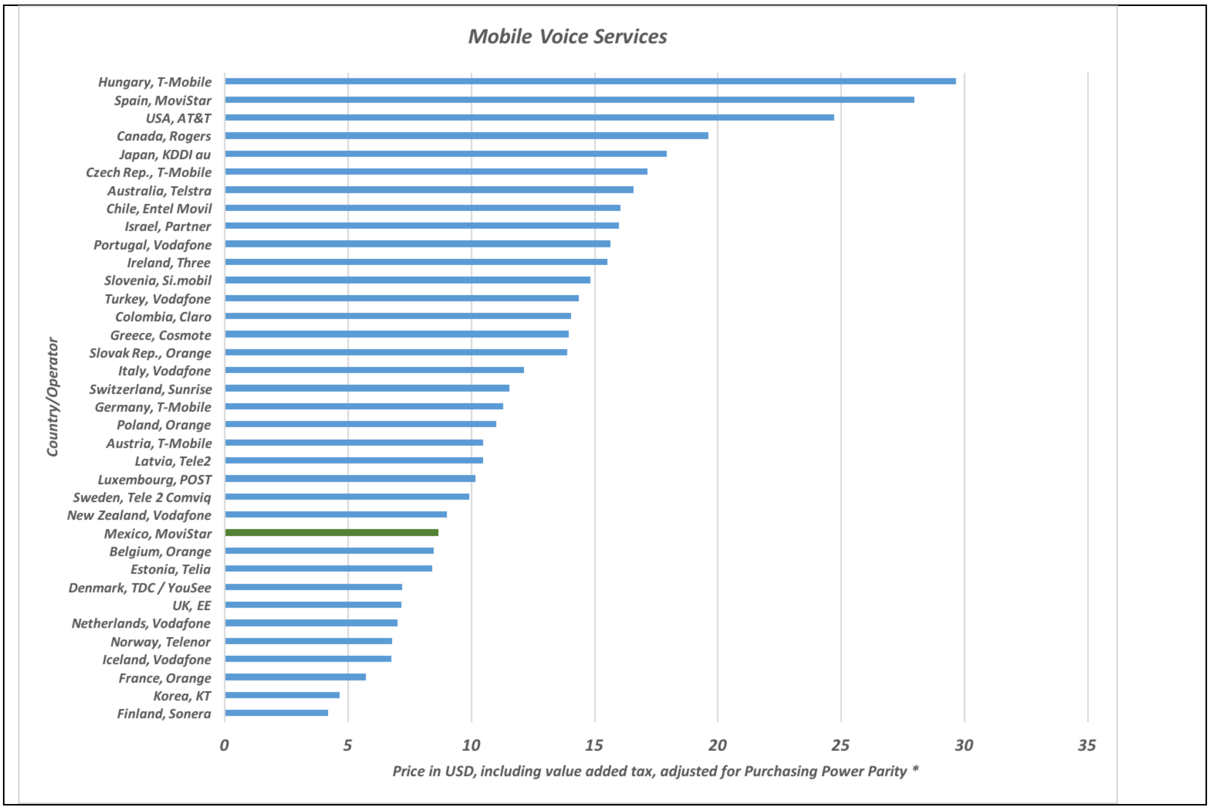
Source: INEGI (2016).

Figure 1b Evolution in mobile telecommunications CPIs in Mexico. 2011-2016.



Source: Own elaboration with data from Strategy Analytics (2016). The prices are for call baskets, as defined by the cited source.

Figure 2a Fixed voice prices for selected operators from OECD countries. 2016.



Source: Own elaboration with data from Strategy Analytics (2016). The prices are for call baskets, as defined by the cited source.

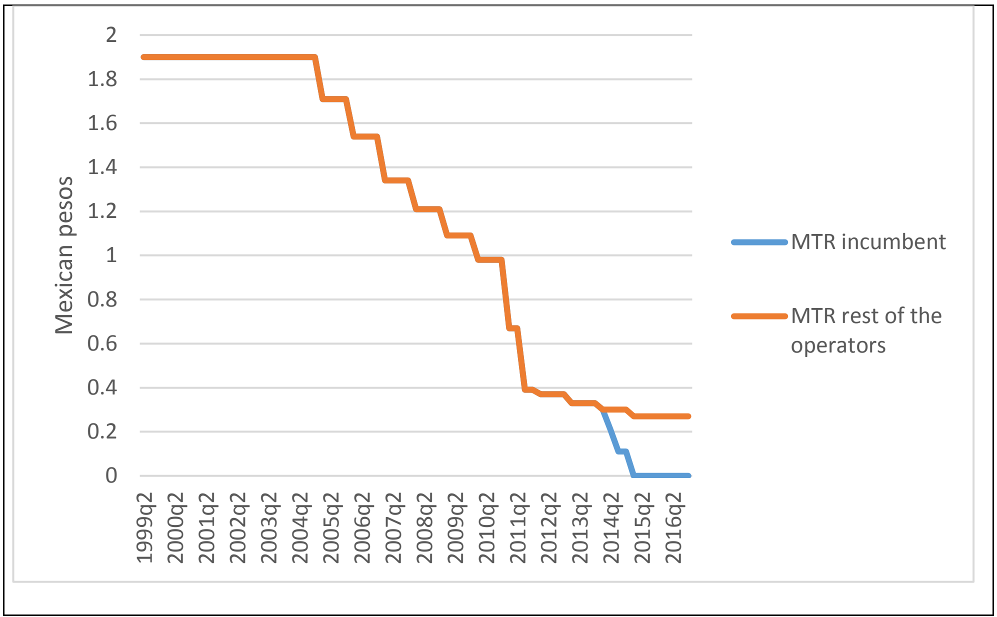
Figure 2b Mobile voice prices for selected operators from OECD countries. 2016.

In addition, Mexico's constitutional reform in telecommunications and broadcasting has resulted in achievements that have a direct, positive impact on consumers. Examples are the elimination of long distance fees for national fixed and mobile voice calls, the improvement of number portability rules and the requirements for all operators to provide consumers with information on the conditions and performance of the telecommunications and broadcasting services that they are hiring.

Asymmetric regulation

Interconnection pricing stood out as an item for reform because, even though under perfect competition interconnection rates should correspond to the cost structure of the operator offering access to its network, there is evidence that their fixing corresponds more to the strategic and competitive behaviour of firms. This usually happens because interconnection rates are an instrument that can be used by larger networks to generate club effects and attract more subscribers (Castro et al, 2013; Laffont et al, 1998; Harbord & Pagnozzi, 2010). In practice, the cost structures end up being affected by the levels of competition, and dominant operators may end up strengthening their position in the market. For these reasons, a number of research studies point to the importance of regulating interconnection rates as a mechanism to increase levels of competition in mobile telephony markets. For example, Laffont & Tirole (2000) maintain that a good interconnection policy is key to the development of competition in telecommunications markets (Castro et al, 2013).

Taking this into consideration, the LFTR (article 131) now includes specific provisions dealing with interconnection rates for "preponderant" economic agents. An economic agent is considered as "preponderant" in terms of its national participation in the provision of broadcasting or telecommunications services, if it has a market share greater than fifty per cent. In accordance with the Law this percentage can be measured by the number of users, subscribers, audience and traffic or capacity in their networks, depending of the adequacy of the metric to reflect the competition in the corresponding market. For such agents, the regulator can impose ex-ante measures including a prohibition for operators to charge for interconnection as long as they meet the criteria to qualify as preponderant economic agents. Figure 3 shows the evolution in Mobile Termination Rates (MTRs) and the asymmetry between them. In fact, Escobar-Briones (2016) provides evidence on how the implementation of asymmetrical MTRs has translated into lower prices, increased consumption and therefore more consumer welfare for Mexican consumers.



Source: Own elaboration with data from Bank of America-Merril Lynch (2014), Del-Villar-Alrich (2006) and Ovum TMT Intelligence Informa (2017).

Figure 3 Evolution of MTRs in Mexico.

Infrastructure competition

In most OECD countries, open access policies for fixed networks in the form of mandated regulated access, such as local loop unbundling or other wholesale access products, have played a leading role in the development of competition, as these markets were liberalised (OECD, 2013). The relevant Mexican regulatory framework establishes the following. The LFTR, in its 138th article, mandates that each year the "preponderant agents" must register (with the IFT) and publish their list of interconnection services in a disaggregated manner. They are required to provide the technical and functional specifications of the interconnection points and to publish reference interconnection offers, indicating the elements that are available for such purpose, in accordance with article 267 of the LFTR.

Article 3 establishes that the IFT is responsible for determining which inputs are to be considered essential, in accordance with the Federal Economic Competition Law (*Ley Federal de Competencia Económica*) (Article 94). Article 128 of the LFTR, on interconnection and obligations for the "preponderant", and article 267, on preponderance, specify obligations that such an agent faces in relation to the disaggregation of its network and the provision of services to other concessionaries. Article 138 states that the preponderant must share infrastructure, co-location sites and rights of way. In addition, article 139 establishes that the IFT will promote infrastructure sharing, the service of co-location between concessionaries and rights of way when they are limited by reasons of public interest, or legal or regulatory provisions. The issues addressed through these provisions were part of a more general problem that has already been notified: the then lack of development in the broadband sector.

Besides the competition legislation to improve broadband penetration (most notably the increase in mobile broadband penetration, from 46% to 56% between 2015 and 2016 (IFT, 2016b)), a fundamental initiative has been introduced by the Mexican authorities to maintain this positive trend. This is the development of a wholesale national broadband wireless network (*red compartida*), a new Public-Private-Partnership project whose contract has been awarded and is set for implementation starting in 2017. It is part of a broader digital inclusion strategy (Article 3, LFTR) and has the objective of increasing telecommunication services coverage, for which purpose it includes a minimum coverage requirement which was set at 85% of the national population (SCT, 2016).

This project also represents a further step in a series of coverage obligations that have been established in the country. As a consequence of the reform, specific actions in terms of social telecommunications coverage have resulted in a comprehensive national connectivity plan, called *Programa de Conectividad Digital (*SCT, 2017). It combines the goals of a series of projects, including a brand new system of Mexican next-generation satellites (*Sistema Satelital Mexicano Mexsat*), a public sites-internet hotspots project (*México Conectado*), access to government telecommunications facilities for private networks (*proyectos de infraestructura pasiva del Estado*) and a national high capacity network for scientific, technological and educational research (*Red NICTE*).

Another milestone in the digital inclusion strategy comprises a number of articles in the LFTR (3, 74, 79 and 81), which establish that licences for the provision of telecommunications and broadcasting and for the use of radio spectrum will be granted preferably to those who incorporate specific factors. Examples include plans and commitments in terms of minimum coverage and their contribution to universal service goals.

Regarding the licencing model for operators to provide their services, the new Law created a convergent telecommunications licence called *Concesión Única,* authorising the provision of all facilities-based services (telephony, video, Internet, etc.) under one single licence (McCutchen, 2014). Potential benefits of this measure include, on the one hand, that competition between networks may become more effective and, on the other, that any individual network can provide access to a greater range of services than previously. This leads to potentially much stronger economies of scale and scope than before (ITU, 2013). Furthermore, the *Concesión Única* seeks to reduce regulatory costs and to incentivise operators to maintain technological evolution of their network in order to be able to provide more diversified services (SCT, 2006).

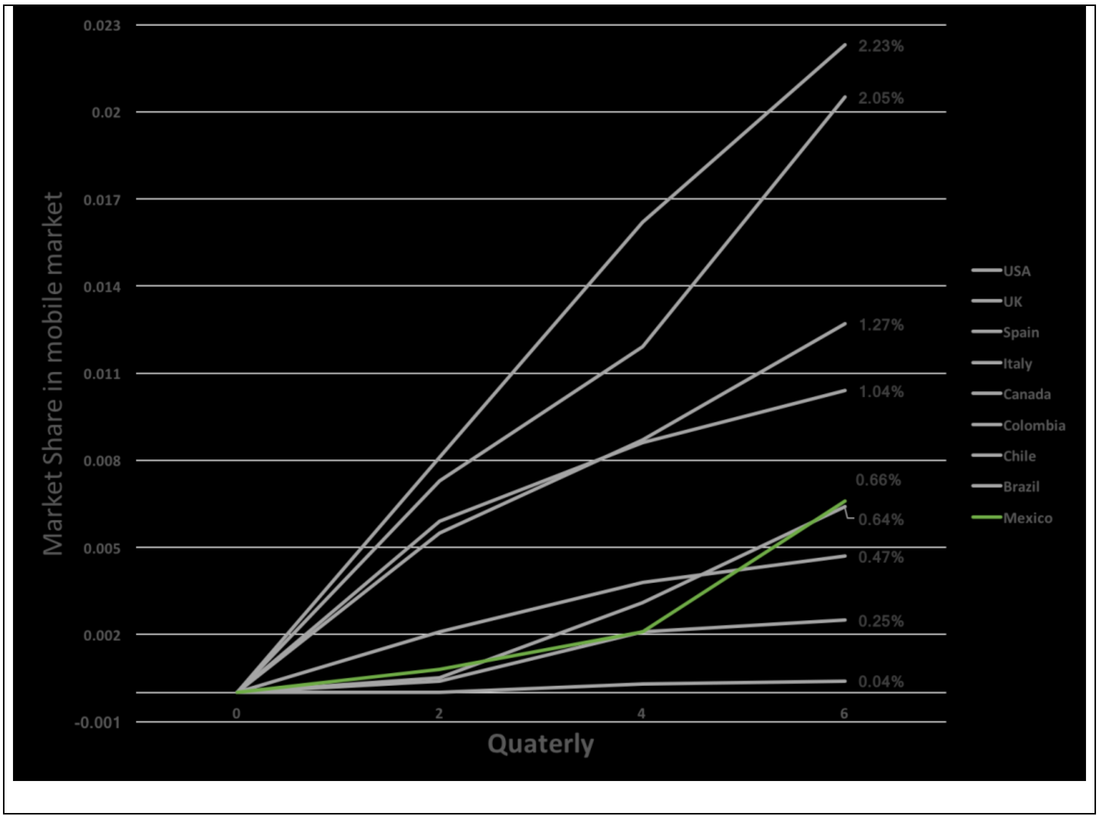
In terms of infrastructure access provisions, the possibility of mobile network operators (MNOs) to host MVNOs as a means of improving competition was also among the suggestions made by OECD for Mexico. The OECD considers that the entry of MVNOs, either through voluntary agreements with MNOs or by some type of mandated regime, has improved the level of domestic competition in other countries (OECD, 2013). With this in mind, the IFT has issued guidelines that facilitate the licensing of MVNOs, defined as new providers of mobile services, which use the capacity and/or services provided by MNOs, to operate in certain frequency bands of the radio spectrum (IFT, 2016c). The list of MVNOs that operate in the country is included in Table 1. Some examples are worth noting because they have emerged as part of the following synergies:

QBOCEL – In August 2014, the company KUBO CEL S.A.P.I. de C.V. was granted permission from IFT to provide telephony and data transmission through the QBOCEL brand, owned by the national union for education workers (*Sindicato Nacional de Trabajadores del Estado*, commonly referred to as SNTE).

Cierto – In alliance with Ekofon, OXXO, a Mexican chain of convenience stores, has entered the mobile market through the MVNO “Cierto”. This operator is currently providing its services in the Mexican market, with authorisation from the regulator.

Weex – This operator provides its services through Telefonica’s network (Movistar). It was launched as a start-up by students of the *Instituto Tecnológico y de Estudios Superiores de Monterrey*. The start-up was supported by the Coca-Cola Company.

In spite of low initial penetration levels, especially as compared to other economies, the number of subscribers to MVNOs’ services has been increasing in Mexico (Figure 4). Further development of this type of operators is expected to be triggered by the deployment of the wholesale wireless network *Red Compartida* (IFT, 2016e).



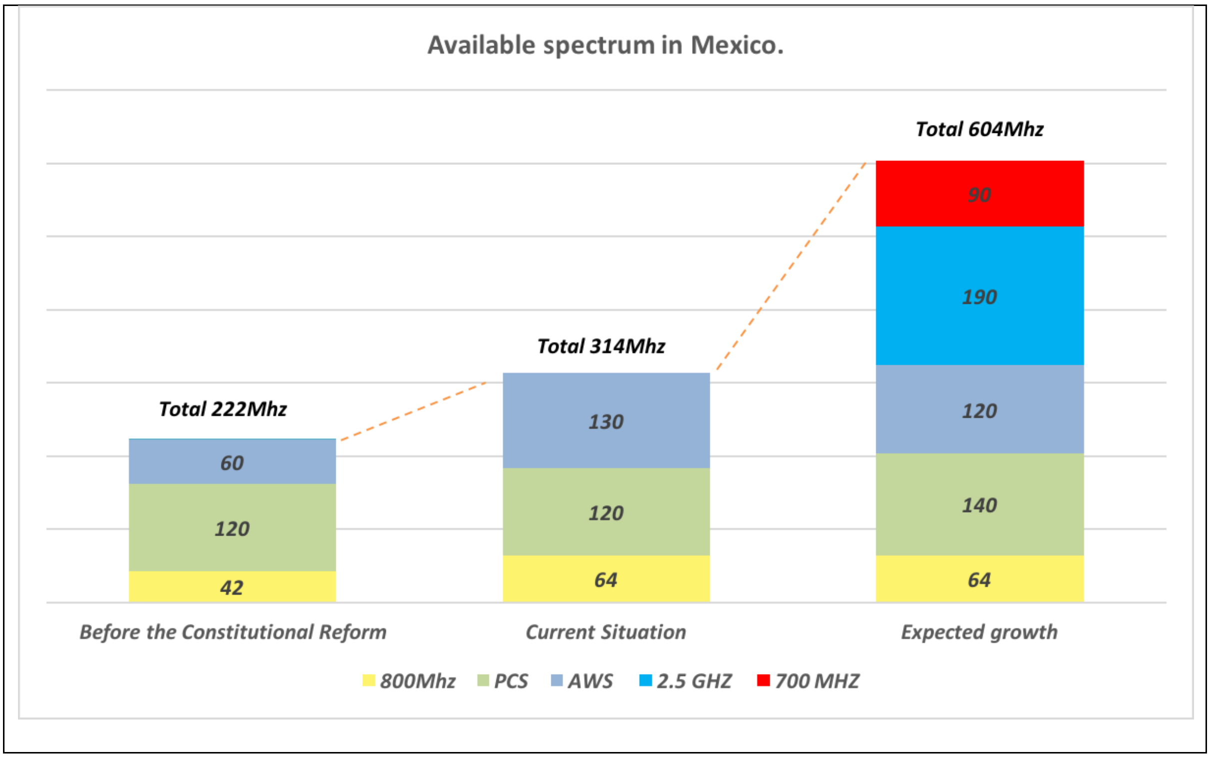
Note: Time in the "x" axis has been normalised to the starting period (entrance of MVNOs) for each country.
Source: Own elaboration with data from IFT (2016e).

Figure 4 International comparison of growth in MVNOs' market share.

Radio spectrum

It is well known that radio spectrum is a fundamental input for telecommunications services, which is why concerns were raised concerning its availability. According to Hazlett & Muñoz (2009), greater spectrum availability can lead to diminishing prices and reduced market concentration. The unequal distribution of spectrum among the different operators has also been identified as a determinant of market concentration (Saenz-de-Miera-Berglind, 2015), whereas the differences in terms of frequency-bands has been associated to mobile services penetration (Robles-Rovalo, 2016).

With this in mind, increased spectrum allocation has taken place in Mexico over the last years. More specifically, an AWS spectrum auction was carried out in 2015 and the first digital dividend has been already completed, allowing for 90 MHz in the 700 MHz band to be committed to the operation of the new wholesale national network. Also, the IFT expects to auction the 2.5 GHz band during 2017 and clear the 600 MHz band by the end of 2018. Figure 4 shows the projected amount of spectrum that is expected to be assigned among the operators in the future, based on a scenario suggested by IFT. Under this scenario, Mexico could catch up with countries that are currently ahead of it, such as Brazil, Chile, Nicaragua, Panama, Argentina, Colombia, Puerto Rico and Venezuela.



Source: Own elaboration with data from IFT (2016b).

Figure 5 Mobile Spectrum scenario in Mexico (2018).

The distribution of spectrum among the operators was brought to the attention of the authorities as well. In 2012 the OCDE (2012) pointed out that the spectrum assignment processes should be designed carefully in order to avoid a situation in which one company dominates this market. For this reason, the first two AWS auctions (numbers 20 and 21) were carefully designed.

However, once the constitutional reform had taken place, the regulator sought to improve the design of the new AWS auction, with respect to the previous AWS auctions, which had taken place prior to the reform (Rodríguez, 2015a). The regulator did this by implementing a combinatorial clock auction, in an effort to adhere to international best practices. Furthermore, the authorities recognised that the spectrum cap is one of the main design components that can influence stakeholders' interests and the value of spectrum, which in turn has direct implications for the prices paid at auctions, the business prospects for new networks and the impact of broadband services on society (ITU, 2012). Therefore, auctions number 20 and 21 had already incorporated the use of caps and "set-aside" mechanisms for new entrants. However, the caps and set-asides for these auctions were set by regions (in Mexico the use and exploitation of spectrum is divided according to nine geographic regions (IFT, 2016d)), whereas the AWS auction was designed with the use of caps that considered the prior distribution of spectrum among the operators.

The spectrum management measures that have been implemented since the constitutional reform also consider the possibility of a secondary spectrum market (SEGOB, 2017), as well as those of refarming and reallocation of different spectrum bands (AM, FM, 450 MHz, 600 MHz, 700 MHz, 800 MHz, AWS, 2500 MHz, 3500 MHz).

Investment

Infrastructure investment was identified as another area for policy improvement. It is well known that regulatory certainty and transparency are key determinants of investment levels. An area where regulation was considered by the OCDE (2012) to act as an obstacle to investment in Mexico was the limit imposed on the level of foreign direct investment in the country. For this reason the constitutional reform has resulted in foreign direct investment of up to 100% now being allowed in telecommunications and satellite communications. In fact, investment levels have increased in Mexico after the constitutional reform (IFT, 2016b) and are expected to keep growing with the introduction of the wholesale broadband network, and with diverse upgrades and joint initiatives by the operators in the evolution to next-generation-networks (Forbes, 2016; Guerrero, 2015; Rodríguez, 2015b).

A point worth mentioning in regard to network upgrades is gigabit technology. Even though there is no specific national governmental program to upgrade gigabit networks, nation-wide-operators are continually upgrading their backbone networks and offering gigabit connections to Small and Medium Enterprises. Additionally, there are projects by academic, entrepreneurial and private-operators networks that provide gigabit transmission capabilities and interconnect major cities (CUDI, 2016). Currently, there are specific efforts to accurately identify and assess the level of deployment and evolution of gigabit technologies in Mexico, such as the National Registry of Infrastructures (*Registro Nacional de Infraestructuras*), a database that will record the attributes of telecommunication networks in the country (IFT, 2017a).

Digital economy

Finally, the national authorities have endeavoured to open up future opportunities with the development of the digital economy. For example, citizens' access to ICTs, telecommunications and broadcasting services, including broadband Internet access, is now a constitutional right. A National Digital Strategy has been defined, which is being implemented so technology and innovation can contribute to reaching the country's development goals. Its objectives are the digital transformation of government processes and policies and the ways to interact with government; development of the digital economy; digital transformation of access to education and health systems; civic innovation and citizen participation. These types of initiatives are expected to enable the country to benefit from the digital economy, and to face the potential obstacles arising, especially from the regulatory standpoint.

Conclusions

The characteristics that had defined the traditional Mexican telecommunications market raised a series of concerns that resulted in the 2013 constitutional reform. This reform has laid the foundations for an improvement in competitiveness in the sector, to achieve the national benefits identified as essential objectives by the Mexican Government. With the measures implemented since the reform came into effect, it is evident that providing the telecommunications regulator with adequate powers has been crucial in creating effective competition. In fact, this has translated into favourable outcomes that have begun to be tangible. However, the Mexican authorities need to continue with their efforts, given that Mexico is no exception to the universal challenges posed by rapid technological change and the transition to a digital economy.

At the time of writing, the IFT has finished its first assessment of the measures imposed on the "preponderant" economic agent (IFT, 2017b). Based on economic analyses and public, technical and legal consultation processes, the assessment presents key issues that include the following: the growth in fixed broadband penetration has been lower than expected; broadband speeds are still below the OECD average; there is a low level of infrastructure based competition; and 12% of the population still does not have access to fixed services. These figures have been attributed to the fact that even after the implementation of the measures for the "preponderant", its competitors have had limited or slow access to its infrastructure and unbundling services, due to incentives to delay negotiations and increase transaction costs. Accordingly, the IFT has determined that to be able to continue pursuing the goals of the constitutional reform, it is necessary to impose functional separation measures. The objective is to ensure non-discriminatory conditions in the provision of wholesale services, for market participants to be able to compete under the same conditions. This measure poses new challenges that deserve future research and will play a key role in the future evolution of the sector.

Acknowledgements

The authors acknowledge and thank the valuable and enriching comments from Pascual García-Alba Iduñate (*Centro de Estudios*, IFT), who does not share any responsibility for any flaws in the article. The views and conclusions presented in this article are the exclusive responsibility of the authors and do not represent those of the IFT.

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http://doi.org/10.18080/ajtde.v5n1.84

A New QoS Routing Northbound Interface for SDN

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Abstract: In this paper, we introduce SCOR (Software-defined Constrained Optimal Routing), a new Software Defined Networking (SDN) Northbound Interface for QoS routing and traffic engineering. SCOR is based on constraint-programming techniques and is implemented in the MiniZinc modelling language. It provides a powerful, high-level abstraction layer, consisting of 10 basic constraint-programming predicates. A key feature of SCOR is that it is declarative, where only the constraints and utility function of the routing problem need to be expressed, and the complexity of solving the problem is hidden from the user, and handled by a powerful generic solver. We show that the interface (set of predicates) of SCOR is sufficiently expressive to handle all the known and relevant QoS routing problems. We further demonstrate the practicality and scalability of the approach via a number of example scenarios, with varying network topologies, network sizes and number of flows.

Keywords: Constraint Programming, Software Defined Networking, Northbound Interface, Quality of Service Routing, MiniZinc.

1. Introduction

Software Defined Networking (SDN) aims to improve network programmability, simplify network management and enhance network operation. It represents a paradigm shift in networking that decouples the control plane from the data plane, and places the control of the system in a logically centralised node, called *SDN controller*. Consequently, the SDN controller has a global view of the network, which facilitates the rapid development and deployment of new network services and applications (McKeown 2009). The SDN architecture consists of three layers, i.e. infrastructure, control and application layer. The control layer (SDN controller) provides key abstractions and network services for the application layer through the *northbound interface*. There is a range of SDN northbound interfaces with various functionalities, but no dominant standard has evolved so far (Kreutz et al. 2015).

Today's networking environment necessitates using various *Quality of Service (QoS)* routing and *Traffic Engineering (TE)* techniques to optimise the traffic flow for different applications and traffic types, e.g. voice and video. The implementation of these QoS routing and TE applications, which can be complex, is not readily supported by current northbound interfaces. Despite the vital importance of these applications in networking, they still require a lot of low-level effort and a high degree of skills in order to be implemented in SDN.

In order to address this gap, this paper introduces a new SDN northbound interface. This interface is based on *Constraint-Programming (CP)* techniques to provide Software-defined Constrained Optimal Routing (SCOR). The main idea behind using CP methods in SCOR is to provide a level of abstraction and hide the complexity from the user.

In CP, users only state the constraints that the solution should have, and do not specify a step-by-step solution of the problem, as in the case of procedural programming. In other words, in CP users are only concerned with expressing or declaring the problem, and not with its solution. The solution is provided by a powerful general-purpose CP *solver*. SCOR provides an interface for expressing QoS routing applications, consisting of nine basic building blocks, i.e. *predicates*. We show in this paper that this interface is able to model both simple and complex QoS routing problems, in a very simple and compact manner. The scalability of SCOR is also evaluated through a number of example applications and a number of experiments.

SCOR is explained after a brief background in Section 2, and a short review on related works in Section 3. Section 4 explains the architecture of SCOR, and Section 5 and Section 6 describe its implementation and use cases. Section 7 discusses the evaluation methodology and results and Section 8 concludes the paper.

2. Background: Constraint Programming

Constraint-Programming (CP) techniques were initially introduced in the 1960s and 1970s in artificial intelligence and computer graphics. They have found applications in many fields such as operations research, programming languages and databases (Rossi et al. 2006). The main idea behind CP is to separate the expression of a problem from its solution. Users are only required to state the problem and the solution is found by general-purpose constraint solvers which are designed for this purpose.

This allows for very flexible modelling of problems and their efficient solution, for large, particularly combinatorial problems (Bartak 1999). In order to use CP to solve a real world problem, it must be stated in the form of a *CP model*. A CP model includes at least three parts:

- *Decision variables* that represent tasks, metrics or resources of a real world problem.
- *Variable domains* that are a finite set of possible values for each decision variable.
- *Constraints* that state the relations (conditions, limitations, properties and bounds) between decision variables.

The constraints in fact restrict the values that all decision variables can have for a particular solution (Bartak 1999). The solution of a CP model is the allocation of values to the decision variables from their domains that simultaneously satisfy all the constraints. Accordingly, CP problems are called *Constraint Satisfaction Problems (CSP)*. The solver can provide a single solution, the first one that satisfies the constraints, all possible solutions, or the one that maximises or minimises a provided objective function.

If an objective function is defined, the problem is called a *Constrained Optimisation Problem (OP)* (Bartak 1999). The solvers enumerate possible variable-value combinations intelligently and search the solution space either systematically or through some forms of complete or incomplete search methods. The performance of these methods depends on the nature and statement of the problem (Rossi et al. 2006).

3. Related Works

Different types of classifications are proposed for QoS routing in legacy networks. The classification shown in Fig. 1 is proposed by Chen & Nahrstedt (1998). It divides the unicast routing problems into two major categories: *basic* and *composite* routing problems. The criterion used for this classification is the *number of QoS metrics* applied in the problem. A basic routing problem includes only a single QoS metric such as delay, jitter or bandwidth. The routing problem in this case might consist of *metric optimisation*, such as finding a minimum delay path, or it might include *metric constraining*, such as finding a bandwidth-constrained path. In addition, the metric might be related to a *link parameter*, e.g. bandwidth, or it might be related to a *path parameter*, such as end-to-end delay. The composite routing problems represent multi-constraint QoS routing problems. They can be expressed as the combination of a single-metric-optimisation problem with one or more metric-constraining problems, or just the combination of two or more metric-constraining problems.

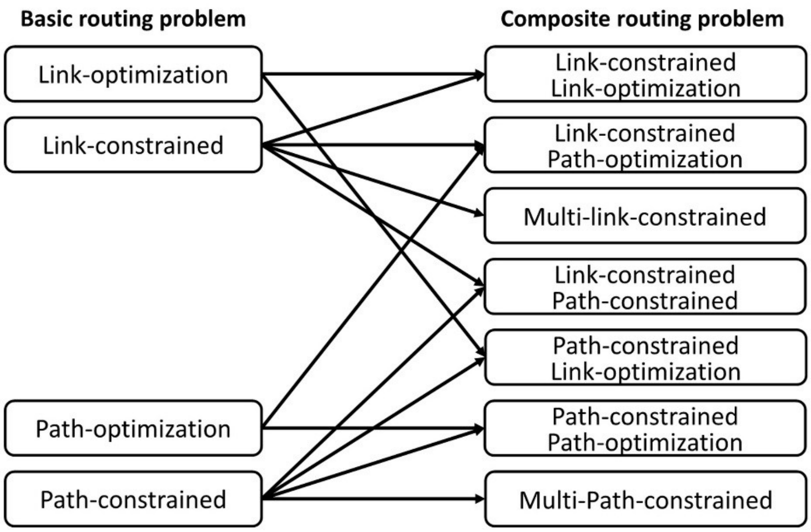

Figure 1 : Basic and composite QoS routing problems (Chen & Nahrstedt 1998)

In SDN though, limited work has been done on QoS routing problems. Indeed, there is currently no northbound interface that provides the required abstractions for implementing all the above basic and composite QoS routing algorithms. While there exist a number of controller-proprietary northbound interfaces, they tend to deal with packet and port-level manipulations rather than higher-level routing and QoS routing abstractions. The PANE controller (Ferguson et al. 2013) and SFNet northbound interface (Yap et al. 2010) are two examples of implementing QoS abstractions in SDN. However, their limited functionality and scope restricts the range of QoS routing applications that can be implemented.

DEFO (Hartert et al. 2015) is a recent approach to control forwarding paths in *non-SDN* carrier grade networks. It uses CP for network optimisation and to efficiently address QoS routing requirements. Using CP and new heuristics has enabled DEFO to achieve a significant increase in scalability and flexibility in traditional networks. While DEFO includes features for expressing QoS routing and TE requirements using CP, it has not been designed for SDNs, and does not provide a suitable northbound interface. In this paper, we are trying to address this gap, by providing a new northbound interface in SDN that facilitates development of QoS routing and traffic engineering applications in an efficient and scalable way.

4. Architecture

Fig. 2 shows the integration of SCOR in the SDN architecture, between the application and control layer. SCOR consists of two layers which represent two levels of programming abstractions. The bottom level is the generic *CP-based Programming Language* and the higher level is the set of *predicates* which form the *QoS Routing and TE Interface*. The second layer, the QoS routing and TE interface, is specifically designed to address QoS routing and TE requirements. It consists of 10 building blocks or predicates, as listed in Table 1.

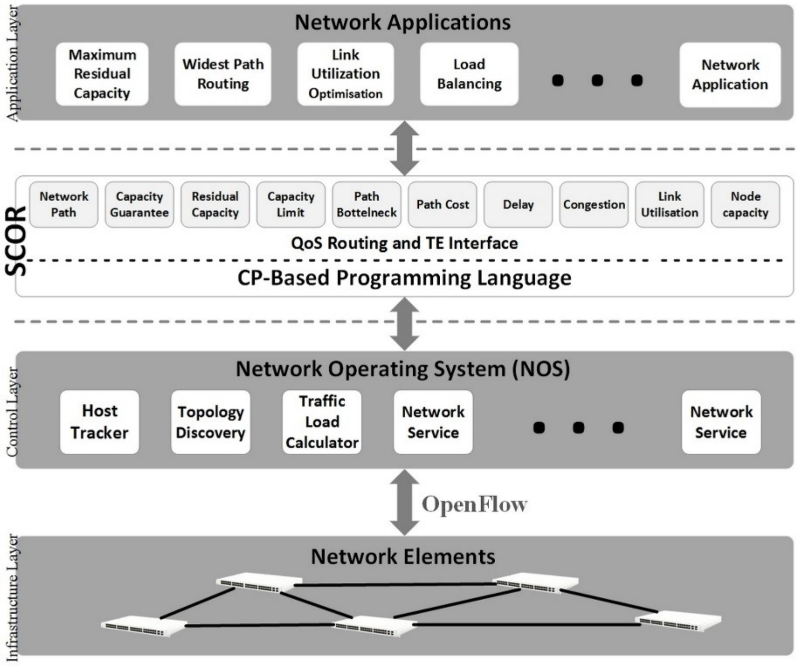

Figure 2 : Situation of SCOR in the SDN architecture

The most basic concept in routing that we need to model in SCOR is that of a *network path*, i.e. a sequence of links which connect two nodes. The *network path* predicate defines a loop-free path from a flow source to its destination. The rest of the predicates implement other constraints which are required in QoS routing applications such as *capacity constraint* and *cost*. These are the required building blocks for modelling both basic and composite routing problems as seen in Fig. 1.

The *capacity guarantee* predicate implements the capacity constraint, which guarantees flows are placed only on links that can accommodate them. Whenever flow demands are considered in a QoS routing application, knowing the available capacity in the network is necessary for accommodating them. The *residual capacity* predicate is created to provide these values by defining the residual capacity of all links, assuming all the known flow demands are routed. The *capacity limit* predicate removes links with a capacity less than a specified limit from the path calculation. The *path bottleneck* predicate defines the bottleneck capacity for a given path, which is required when considering the bandwidth optimisation problem in QoS routing. The path cost, a frequently utilised networking concept, is modelled by the *path cost* predicate.

http://doi.org/10.18080/ajtde.v5n1.91

It is possible to assign various parameters for the cost, such as loss, delay, round trip time (RTT), number of hops, etc.

Table 1: Set of predicates forming QoS routing and TE interface of SCOR

Item	Predicate Name	Functionality
1	*network path*	Defines the paths from a flow source *s* to a flow destination *t*
2	*capacity guarantee*	Applies the capacity constraint on flows in a given graph
3	*residual capacity*	Defines the residual capacity of links of a graph for a set of flows
4	*capacity limit*	Removes all links with a capacity less than a specified value
5	*path bottleneck*	Declares the bottleneck capacity of a flow path in a given graph
6	*path cost*	Defines the total cost of a flow path in a given graph
7	*delay*	Defines the queueing delay for the given set of flows and graph
8	*congestion*	Defines the congestion for the given set of flows and graph
9	*link utilisation*	Defines the link utilisation for the given set of flows and graph
10	*node capacity*	Applies the constraint on the total flows entering or exiting nodes

There are TE problems in which the desired network parameters dynamically change with the traffic. For instance, the queueing delay in each network node not only depends on the capacity of network paths, but it also depends on the amount of traffic flowing into the network. These TE applications which are mostly defined based on the residual capacity concept are covered by the *delay*, *congestion* and *link utilisation* predicates.

The last predicate, node capacity, is designed to model the half-duplex transmission nature of many wireless networks, as well as other shared media access networks. In the half-duplex transmission mode, a node can either send or receive data, but not both simultaneously. This can be stated as "the capacity of a half-duplex node to send the traffic is reduced by the amount of traffic it is currently receiving". It is possible to implement this concept or constraint in a range of ways, we have implemented it via imposing a total capacity constraint per node (i.e. network interface card), considering both ingress and egress traffic. This constraint is imposed in addition to other constraints, in particular the link capacity constraint.

5. Implementation

SCOR is implemented in MiniZinc (Nethercote et al. 2007) which is a declarative CP modelling language. It comes with a set of pre-packaged solvers, but it can easily use other solvers as well. The ease of implementation, simplicity, expressiveness and compatibility with many solvers has made it a good choice for the basis of SCOR. MiniZinc includes a rich library of *global constraints* which model high-level CP abstractions (Nethercote et al. 2007). A problem is stated in MiniZinc in two parts, the *model* and *model data*. The model uses *parameters*, *decision variables* and *constraints* to describe the structure of a CP problem. The model data includes the values of static parameters that are determined when the problem is defined, e.g. in a separate file. The values of decision variables are undecided and they are determined by the solver. Different model data can be used with a single model to designate various problem scenarios (Nethercote et al. 2014). MiniZinc includes *predicates* that are similar to functions or methods in procedural programming languages for creating abstractions, modularity and code reuse. Predicates define higher-level constraints and can be included in a model using an *include item* (e.g. **include** *"globals.mzn";*). MiniZinc expressions, syntax and a wide range of examples are explained in detail in the MiniZinc tutorial (Marriott et al. 2014).

Using the above-mentioned MiniZinc concepts, we can define the *network path* predicate, which plays a fundamental role in SCOR. The network path predicate uses the flow conservation concept to define a flow path. The flow conservation rule is explained as follows. We assume a directed graph $\mathsf{G}(\mathsf{N},\mathsf{L})$ representing a network topology.

The set of network nodes is represented by N and $\mathsf{L} = \{(u,v) \mid u,v \in \mathsf{N}\}$ represents the graph arcs i.e. network links. Links are assumed multi-weighted with the weights being scalars representing various link parameters such as capacity, delay and cost. The flow $f(u,v)$ of a link (u,v) defines the quantity of units, e.g. expressed in Kbps or Mbps, which flows between a source u and a destination v. Given the directed nature of G, $f(u,v)$ is not necessarily the same as $f(v,u)$. With this, the flow conservation rule can be stated as follows:

$$\sum_{\{v|(u,v)\in\mathsf{L}\}} f(u,v) - \sum_{\{v|(u,v)\in\mathsf{L}\}} f(v,u) = \begin{cases} 1 \;\; if \;\; u = s, \\ -1 \;\; if \;\; u = t, \\ 0 \; otherwise \end{cases} \quad (1)$$

Eq. 1 states that for a unit flow, except for the source s and destination t, the sum of the flows arriving at each node is equal to sum of the flows leaving it. This constraint defines a network path, i.e. a contiguous list of links connecting a source and a destination node.

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The MiniZinc code that defines the flow conservation rule and hence implements the *network path* predicate, is shown in Predicate 1. In this code N_{nodes} and N_{links} represent the number of nodes and links respectively, and s and t are the source and destination nodes of the flow. $Links$ is a 2-dimensional array, with each row representing a link. In our implementation, a row (or link) k consists of the following four elements $[u_k, v_k, w_1, w_2]$, with u_k and v_k representing the source and destination node, and w_1 and w_2 representing 2 link weights. The choice of 2 for the number of link weights is arbitrary, and can easily be extended to any required number. LPM, the Link Path Membership, is an array of binary decision variables, which indicate which links belong to a path. $LPM[i] = 1$ means that link i belongs to a path, and $LPM[i] = 0$ means that it does not.

In lines 2-4 of Predicate 1, the flow conservation rule is applied to all nodes. Line 2 defines the total flow arriving at node i. This is done by summing up the link-path-memberships of the links in which node i is the destination node, i.e. $Links[k,2] = i$. (The Boolean operator $\wedge$ represents conjunction, i.e. logical AND.) Line 3 defines the total flow leaving node i in a similar manner. Line 4 applies the equality constraint of the flow arriving and departing each node, with the exception of the source and destination nodes.

Predicate 1: *network path*

```
1: forall(i in 1..Nnodes) (
2:    node_flow_in[i] = sum(k in 1..Nlinks) (if Links[k,2] = i then LPM[k] else 0 endif)
      ∧
3:    node_flow_out[i] = sum(k in 1..Nlinks) (if Links[k,1] = i then LPM[k] else 0 endif)
      ∧
4:    node_flow_in[i] + (if i = s then 1 else 0 endif) = node_flow_out[i] + (if i = t then 1 else 0 endif)
      ∧
5:    node_flow_in[i] <= 1 )
```

The definition of a path via the flow conservation rule expressed in lines 1-4 does not prohibit routing loops. The additional constraint in line 5, which says that a flow can arrive at a node at most once, guarantees paths are loop free. For simplicity, we have discussed the network path predicate for a single flow only. However, our implementation supports any number of flows.

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Due to lack of space, we only discuss the core predicates here. The complete details of all SCOR predicates and their implementation are available in (Layeghy et al. 2016).

6. Use cases: QoS Routing Applications

6.1 Least Cost Path Routing

In this section, we explain how we implemented basic least cost path routing using SCOR. We use our previously described representation of a network as a graph $G(N,L)$ with multi-weighted links. In least cost path routing, the problem is to find a path with the minimum total cost between a source node s and destination node t (Bertsekas 1998). This can be stated as the following optimisation problem:

$$minimize \quad \sum_{(u,v)\in L} w(u,v)x(u,v) \tag{2}$$

$$x(u,v) \in 0,1$$

subject to

$$\sum_{\{v|(u,v)\in L\}} f(u,v) - \sum_{\{v|(u,v)\in L\}} f(v,u) = \begin{cases} d \;\; if \; u=s, \\ -d \;\; if \; u=t, \\ 0 \; otherwise \end{cases} \tag{3}$$

$$and$$

$$f(u,v) = x(u,v) * d \tag{4}$$

where flow $f(u,v)$ is stated as the multiplication of its demand, d, and $x(u,v)$, a binary variable indicating of whether the link (u,v) is a part of the flow path. The parameter $w(u,v)$ is the weight of link (u,v) which represents the link cost. In practice, these cost values can be used to represent various link parameters such as delay, lease price, packet loss ratio, etc. This makes it possible to model the corresponding QoS routing algorithms in SCOR.

The solution of the problem can be stated as a sequence of links that connects the flow source to the flow destination and has the minimum sum of link costs. Several algorithms such as Dijkstra and Bellman-Ford can efficiently solve this problem in procedural programming (Mir 2014). In SCOR though, the implementation only includes the declaration of the problem, and not how to solve it, as it can be seen in Model 1. Lines 1 and 2 are *include items* which make it possible to use two predicates, network path and path cost. Lines 3-7 declare the *parameters* which are required to model the least cost path problem. The *Links* array/matrix not only states the links start and end nodes, but it also states the corresponding values of link cost and capacity. Lines 8-9 also declare the two decision variables, LPM and $Path\_Cost$. The first variable, LPM, represents the $x(u,v)$ as declared in Eq. 4 and $Path\_Cost$ is the total cost of the flow path.

The main body of the program includes the *Constraints item* (lines 10-11) and the *Solve item* (line 12). The first constraint, network path predicate, defines the path from the flow source node s to its destination node t. The second constraint, path cost predicate, defines the cost associated with the path. The *solve item* indicates the objective, i.e. what the solver should optimise, which is the path cost.

Model 1: *Least Cost Path in SCOR*

```
% Include items
1: include " Predicate network path.mzn";
2: include " Predicate path cost.mzn";
% Parameters
3: array [int,4] of int: Links;
4: int: Nlinks = max(index_set_1of2(Links));
5: array [int] of int: Nodes;
6: int: s;
7: int: t;
% Decision Variables
8: array [1..Nlinks] of var 0..1: LPM;
9: var int: Path_Cost;
% Constraints items
10: constraint network_path(LPM,Links,Nodes,s,t);
11: constraint path_cost(LPM,Links,Path_cost);
% Solve item
12: solve minimize Path_Cost
```

6.2 Least Cost Path Routing with Capacity Constraint

Using SCOR predicates as building blocks, it is easy to state a wide range of QoS routing problems. Here we explain how a new routing application can be defined by adding SCOR predicates to the previously implemented models. For instance, the least cost path routing with capacity/bandwidth constraint problem can be modelled by simply adding a new predicate to the least cost path routing model. In this problem, we are looking for the least cost

http://doi.org/10.18080/ajtde.v5n1.91

path that provides a minimum end-to-end capacity of B . This least cost path routing with capacity constraint problem can be formally stated as the following optimisation problem:

$$minimize \sum_{(u,v)\in \mathcal{L}} w(u,v)x(u,v) \tag{5}$$

$$x(u,v) \in 0,1$$

$subject\,to$

$$\sum_{\{v|(u,v)\in \mathcal{L}\}} f(u,v) - \sum_{\{v|(u,v)\in \mathcal{L}\}} f(v,u) = \begin{cases} d \;\; if \; u = s, \\ -d \;\; if \; u = t, \\ 0 \; otherwise \end{cases} \tag{6}$$

$$and$$

$$f(u,v) = x(u,v) * d \tag{7}$$

$$and$$

$$f(u,v) \le B \qquad \forall (u,v) \in \mathcal{L} \tag{8}$$

where B is the bandwidth/capacity constraint applied to the flow and other parameters are similar to those of the previous model. This is essentially the same as the least cost path routing problem, with the only addition of an additional constraint (8).

Our implementation of this problem is shown in Model 2 which only includes the lines of code added to Model 1. It shows that only three additional lines of code are required to turn the least cost path routing model into the least cost path routing with capacity constraints model. The first added line (line 1) is an *include* item which calls the *capacity limit* predicate. The next added line of code (line 2) defines a new parameter, $Limit$, which states the associated bandwidth/capacity limit or bound. Finally, the last added line (line 3) is the new capacity constraint.

Model 2: *Least Cost Path with Capacity Constraint in SCOR (only lines not included in Least Cost Path model)*

```
⋮
% Include items
1:  include " Predicate capacity limit.mzn";
⋮
% Parameters
2:  int: Limit;
⋮
% Constraints items
```

3: **constraint** capacity_limit(LPM,Links,Limit);
⋮

6.3 Maximum Residual Capacity Routing

The third routing application modelled in SCOR is the M*aximum Residual Capacity* (MRC) routing. Unlike two previous models, this application addresses the problem of routing multiple concurrent flows in a network. The main objective here is to route flows in a network, so that the minimum residual link capacity is maximised. The residual (or available) capacity of a link is the difference between its capacity and the total flow passing through it. Sending a traffic flow in a way that the minimum available capacity of the network is maximised, increases the chance of having sufficient capacity to accommodate the next flow request (Walkowiak 2006).

This is a complex optimisation problem which is also known as the Non-Bifurcated Congestion (NBC) problem, in the context of multi-commodity flow problems. For a set f of K concurrent flows to be routed through $\mathsf{G(N,L)}$ where source of flow f_k is $s_k \in \mathsf{N}$ and its destination is $t_k \in \mathsf{N}$, the problem can be stated as the following optimisation problem (Walkowiak 2006):

$$maximise\ \mathsf{Z} \tag{9}$$

subject to

$$\mathsf{Z} \leq r(u,v) \qquad \forall (u,v) \in \mathsf{L} \tag{10}$$

and

$$r(u,v) = c(u,v) - f(u,v) \qquad \forall (u,v) \in \mathsf{L} \tag{11}$$

and

$$f(u,v) \leq c(u,v) \qquad \forall (u,v) \in \mathsf{L} \tag{12}$$

and

$$f(u,v) = \sum_{k=1..K} f_k(u,v) \qquad \forall (u,v) \in \mathsf{L} \tag{13}$$

and

$$\sum_{\{v|(u,v)\in L\}} f_k(u,v) - \sum_{\{v|(u,v)\in L\}} f_k(v,u) = \begin{cases} d_k & if\ u = s_k, \\ -d_k & if\ u = t_k, \\ 0 & otherwise \end{cases} \tag{14}$$

$$\forall u \in N, k \in 1..K$$

The objective is to maximise Z (Eq. 9), where it is less than or equal to the residual capacity of all links $r(u,v)$ (Eq. 10), subject to the capacity and flow conservation constraints. The residual capacity of the links, $r(u,v)$, is given by (Eq. 11). The capacity constraint (Eq. 12) states the total flow of a link, $f(u,v)$, should be less than or equal to the link's capacity, $c(u,v)$. The total flow of a link, $f(u,v)$, is sum of all individual flows on the link, $f_k(u,v)$ (Eq. 13). Finally, Eq. 14 is the flow conservation rule for a single flow $f_k(u,v)$ with a demand of d_k. In order to implement the flow conservation for individual flows with non-unitary demands, flows are stated as:

$$f_k(u,v) = d_k x_k(u,v),\ x_k(u,v) \in \{0,1\} \tag{15}$$

$$\forall (u,v) \in L,\ \forall k \in 1..K$$

where $x_k(u,v)$ is equivalent to the previously mentioned link-path-membership variable.

A wide range of heuristic solutions for the above problem have been presented in the context of procedural programming, which typically are complex and require many lines of code for the implementation. In contrast, the implementation in SCOR, shown in Model 3, is as simple as the least cost path routing model. The key difference is contained to lines 13 and 14, which implement the residual capacity constraint and state the optimisation objective. Similar to Model 1, lines 1-2 are include items which call two predicates, *network path* and *capacity guarantee*. Lines 3-9 define the parameters such as *Links*, *Nodes*, etc. Line 10-11 declare the two decision variables, *LPM* and *Residuals*, that define link-path-membership and the residual capacity of links respectively. Line 12 implements the *network path* constraint and line 13 implements the *capacity guarantee* constraint which defines the residual capacity and constrains them to be greater than or equal to zero (implementing Eq. 11 and Eq. 12). Finally, line 14 states the objective function, which aims to maximise the minimum of *Residuals* (implementing Eq. 9 and Eq. 10).

Model 3: *Maximum Residual Capacity in SCOR*

```
% Include items
include " Predicate network path.mzn";
include " Predicate capacity guarantee.mzn";
% Parameters
array [int,4] of int: Links;
int: N_links = max(index_set_1of2(Links));
array [int] of int: Nodes;
array [int] of int: Flows;
int: N_flows = max(index_set(Flows));
array [1..N_flows] of int: s;
array [1..N_flows] of int: t;
% Decision Variables
array [1..N_links,1..N_flows] of var 0..1: LPM;
array [1..N_links] of var int: Residuals;
% Constraints items
constraint network_path(LPM,Links,Nodes,s,t);
constraint capacity_guarantee(LPM,Links,Flows, Residuals);
% Solve item
solve maximize min(Residuals);
```

6.3 Wireless Maximum Residual Capacity Routing

The Wireless Maximum Residual Capacity (WMRC) model aims to extend the previous model, by considering the half-duplex nature of many wireless networks nodes. In half-duplex networks, a node can either send or receive, but not both at the same time. This essentially limits the capacity of the node. We have modelled this constraint in the new *node capacity* predicate in SCOR, and we will demonstrate its use for residual capacity routing in wireless (half-duplex) networks.

The mathematical formulation of the problem is similar to previous problem, maximum residual capacity routing, with the addition of the following additional constraint:

$$\sum_{\{v|(u,v)\in L\}} f(u,v) + \sum_{\{v|(u,v)\in L\}} f(v,u) \le C_u \qquad \forall u \in N \tag{16}$$

Here, C_u is the node u capacity/limit that indicates the total traffic flow that a node can handle. This equation constraints the total flows entering and leaving a node to be equal or less than C_u. As mentioned, this extra constraint is implemented in the *node capacity* predicate and is added to Model 3. The implementation of WMRC is shown in Model 4. The first added line (line 1) calls the *node capacity* predicate, the second line (line 2) declares a new parameter, $Node\_Capacities$, which defines the acceptable amount of flows for each node, and line 3 applies the above constraint (Eq. 16).

Model 4: *Wireless Maximum Residual Capacity in SCOR (only lines not included in Maximum Residual Capacity model)*

```
⋮
% Include items
1:  include " Predicate node capacity.mzn";
⋮
% Parameters
2:  array[int] of int: Nodes_Capacities;
⋮
% Constraints items
3: constraint node_capacity(LPM,Links,Flows,Nodes_Capacities);
⋮
```

In order to illustrate how adding the new constraint affects the paths found by the model and consequently the network performance, we use the below scenario. In the network topology shown in Fig. 3, there are three concurrent flows with equal demand of 1 Mbps to be routed from node S1 to node S7. All links are bidirectional with an equal capacity of 1 Mbps in each direction (bidirectional links are mathematically represented using two unidirectional links). (To illustrate the concept, we assume nodes S1 and S7 have no node capacity limitations, e.g. they are equipped with faster or multiple network interfaces.) Shortest path routing, which uses only one of the three equivalent shortest paths from node $S1$ to node $S7$, theoretically can send 1 Mbps as shown in Fig. 4.

For this scenario, the MRC model finds the three paths as the following sequence of links (shown in Fig. 3-a):

- *f1: {(S1,S2),(S2,S6),(S6,S7)}*
- *f2: {(S1,S5),(S5,S6),(S6,S2),(S2,S3),(S3,S7)}*
- *f3: {(S1,S4),(S4,S8),(S8,S7)}*

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The path *f2* is not the shortest possible path from node $S1$ to node $S7$, though, it is a valid path according to the criteria for the maximum residual capacity routing. Although links $(S2,S6)$ and $(S6,S2)$ are both connecting node $S2$ and $S6$, they are considered separate links in full duplex transmission. So the three concurrent flows of 1 Mbps are successfully transmitted to the destination node.

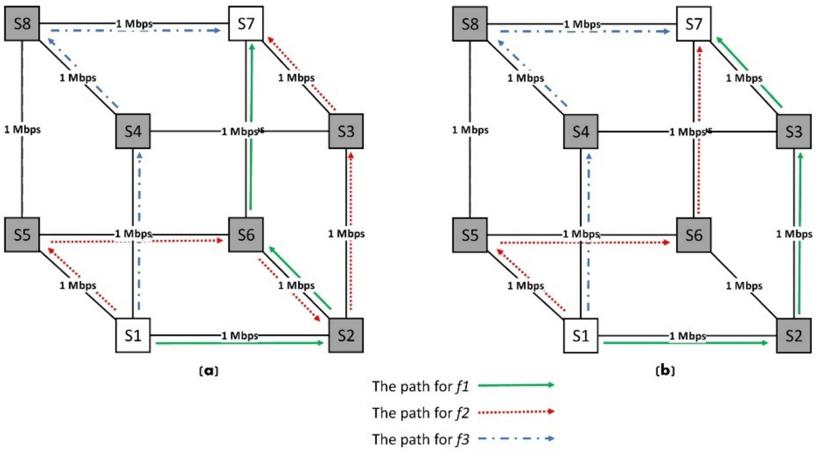

Figure 3: Paths found for three concurrent flows from node 1 to node 7 using a) Maximum residual capacity model (MRC), and b) Wireless maximum residual capacity model (WMRC)

However, in networks which use half-duplex transmission, the situation is different. For these networks, the traffic received by a node limits the amount of traffic that can be simultaneously sent by that node. In this case, the theoretical throughput from node $S1$ to node $S7$, using the three paths found by the MRC model, is only about 2 Mbps, as shown in Fig. 4. The reason for the limited performance in this case is node *S6,* which needs to receive and transmit two flows simultaneously, and hence is the bottleneck.

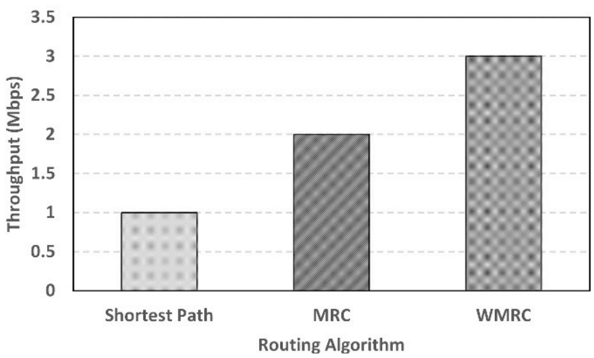

Figure 4: Theoretical throughput for three concurrent flows of 1 Mbps in a half duplex network with a topology as shown in Fig. 3 (node $S1$ is the source and node $S7$ is destination) in the case of Shortest path routing, MRC and WMRC models

Now we use Model 4, WMRC, to find the paths. Since it considers the half-duplex nature of links, modelled as a node capacity limit of 1 Mbps, the WMRC model finds the following three flow paths (shown in Fig. 3-b):

- *f1: {(S1,S2),(S2,S3),(S3,S7)}*
- *f2: {(S1,S5),(S5,S6),(S6,S7)}*
- *f3: {(S1,S4),(S4,S8),(S8,S7)}*

As in the previous case, all links have a capacity of 1 Mbps, and we impose a node capacity limit of 1 Mbps for each node except source and destination, i.e. S1 and S7. As a result of the half-duplex constraint in the WMRC, the impact of node bottlenecks can be minimised, and the aggregate throughput achieved by the above shown 3 paths is 3 Mbps, instead of 2 Mbps of MRC.

This example tries to show how easy it is to add/model new network constraints and features in SCOR, and consequently how easy it is to implement complex QoS routing problems. Our WMRC example is very simple and it only addresses one particular aspect of typical wireless networks, i.e. the half-duplex nature of transmission. The modularity and extendebility of SCOR allows us to easily add further predicates and building blocks, which can model more complex aspects of wireless networks, such as interference.

7. Evaluation

The evaluation of SCOR includes two aspects, the first one being the completeness of the API, i.e. the set of predicates, and its ability to concisely express a wide range of QoS routing problems. The second aspect is the efficiency and scalability of finding valid solutions. The completeness aspect of SCOR was briefly discussed in Section 4. SCOR's set of predicates support the modelling of all QoS routing problems, as classified in Fig. 1. Table 2 shows a list of basic and composite QoS routing problems which we were able to model and solve with SCOR. The table shows the SCOR predicates that were used for each problem, as well as the number of lines of SCOR/MiniZinc code (excluding boilerplate code) that were required for the problem formulation. The *network path* predicate is used in all of these problems and models, and in order to save space, we did not include it in the table.

Table 2: QoS routing algorithms and predicates to model them in SCOR

QoS Routing Problem	**SCOR Predicates**	**#Lines**
Shortest Path	path cost	3
Widest Path (Chen & Nahrstedt 1998)	path bottleneck	3
Bandwidth-Guarantee (Ma & Steenkiste 1997)	capacity guarantee	3
Bandwidth-Constrained (Chen & Nahrstedt 1998)	capacity limit	3
Minimum-Loss (Moreira et al. 2008)	path cost	3
Minimum-Delay (Moreira et al. 2008)	path cost	3
Minimum-Delay (Gallager 1977)	delay	3
Delay-Constrained (Chen & Nahrstedt 1998)	path cost	3
Least-Cost (Chen & Nahrstedt 1998)	path cost	3
Maximum Residual Capacity (Walkowiak 2006)	capacity guarantee	3
Delay-Constrained Least-Cost (Chen & Nahrstedt 1998)	path cost $\times 2$	4
Delay-Delay Jitter-Constrained (Chen & Nahrstedt 1998)	path cost $\times 2$	4
Bandwidth-Delay-Constrained (Chen & Nahrstedt 1998)	capacity limit, path cost	4
Least-Delay Bandwidth-Constrained (Chen & Nahrstedt 1998)	capacity limit, path cost	4
Minimum Cost Bandwidth-Constrained (Patel et al. 2004)	capacity guarantee, path cost	4
Delay-Constrained Bandwidth-Optimisation (Chen & Nahrstedt 1998)	path bottleneck, path cost	4
Widest Shortest Path (Curado & Monteiro 2004)	path bottleneck, path cost	6
Shortest Widest Path (Curado & Monteiro 2004)	path bottleneck, path cost	6

Table 2 clearly shows the expressiveness of SCOR and its power to model complex QoS routing problems. Furthermore, we see that the formulation in SCOR is extremely compact, with a maximum of 4 lines of SCOR/MiniZinc code. This is due SCOR's high level of abstraction.

The second, equally important aspect in the evaluation of SCOR is its scalability and ability to quickly and efficiently find valid solutions to the routing problems. For this, we examined the solve-time of the three implemented QoS routing problems for two network topologies and a

http://doi.org/10.18080/ajtde.v5n1.91

range of network sizes. We considered grid and fat-tree topologies in our experiments. The fat-tree topology we used is defined in (Al-Fares et al. 2008). It is parametrised by k , and consists of three layers, with $k^2/4$ nodes in the core layer, $k^2/2$ nodes in the aggregation layer, and $k^2/2$ nodes in the access layer. Each access node (switch) is connected to $k/2$ hosts.

Fig. 5 displays the solve-time for the Least Cost Path and Least Cost Path with Capacity Constraint routing problems with SCOR. For our experiments, we used MiniZinc's default solver. All experiments were run on a Dell PC with Intel Core i7-4790 CPU and 16 GB of RAM, running Linux with the kernel version of 3.13.0-24-generic. The x-axis shows the network size, and the y-axis shows the solve-time in milliseconds. As can be seen, for both routing problems, the solve time remains below 500 ms, even for relatively large network sizes of greater than 350 nodes. This demonstrates the practical feasibility of using SCOR/MiniZinc to solve complex routing problems in near real time.

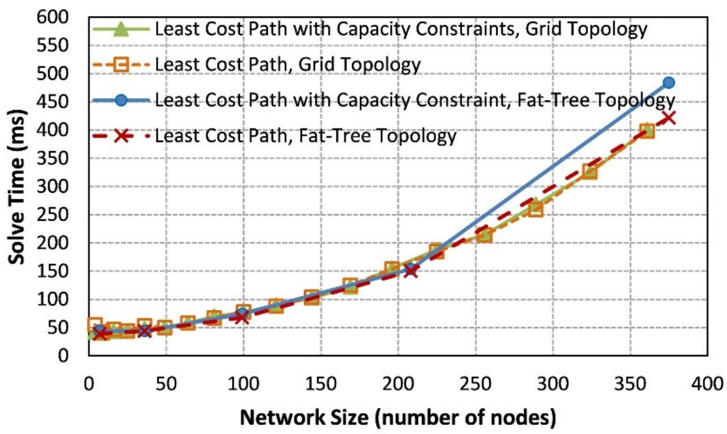

Figure 5: Solve time for the Least Cost Path and Least Cost Path with Capacity Constraint problem in fat-tree and grid topologies with various network sizes

A key benefit of SCOR is that it shields the user from the complexity of solving hard optimisation problems. SCOR leverages the power of highly sophisticated constrained optimisation solvers, such as those provided with MiniZinc. The advantage of our approach is particularly significant for QoS routing problems for which no efficient solution/algorithm exists, and which rely on heuristics. An example is the maximum residual capacity routing problem (Walkowiak 2006).

Fig. 6 compares the solve-time for the maximum residual capacity routing problem in SCOR, with an algorithm using a *linear programming (LP)* approach, presented in Walkowiak (2006). The LP solution is implemented in Python using the NetworkX and PuLP

(Mitchell et al. 2011) libraries. We used the same regular grid and fat-tree topologies of varying sizes as in our previous experiment. As before, the x-axis shows the network size, and the y-axis shows the solve-time in ms. Due to the multiple order of magnitude better performance of SCOR/MiniZinc, we used a logarithmic scale for the y-axis. The LP algorithm was not able to find a solution for a network size of 50 nodes or more, even in a time of 24 hours. In contrast, SCOR/MiniZinc was able to find solutions in under a second, even for networks with more than 350 nodes.

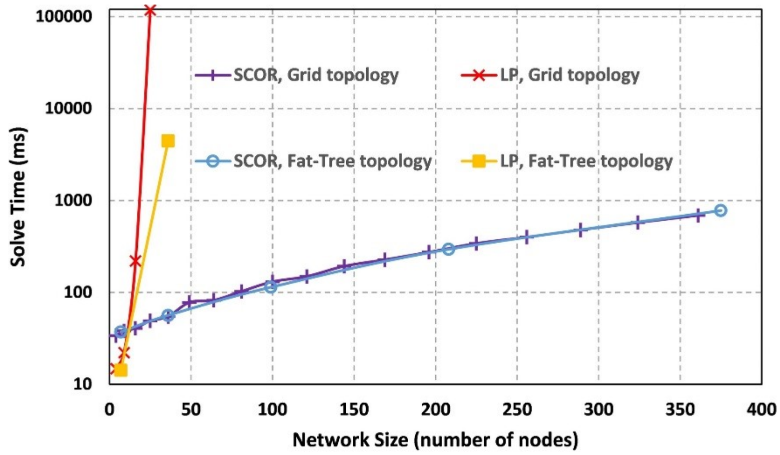

Figure 6: The solution time for the Maximum Residual Capacity problem compared to LP in fat-tree and grid topologies with various network sizes

Hence, SCOR is able to solve complex optimisation problems, such as maximum residual capacity routing, with a speed that is at least as fast as comparable prodecurable programming solutions. The benefit of SCOR lies in the power of its abstraction, its modularity, and simplicity in which complex QoS routing problems can be expressed and solved.

Fig. 7 shows the comparison of solve times of the MRC and WMRC model. The figure compares the solve times for different network sizes and various numbers of concurrent flows in each sub-figures. Fig. 7a compares the solve times for routing a single flow, Fig. 7b two concurrent flows, Fig. 7c three concurrent flows, and finally Fig. 7d compares the solve time for routing four concurrent flows. These results indicate that the added constraint does not increase the solve time significantly, it even reduces the solve time for the WMRC model compared to MRC in some cases (Fig. 7a and 7c).

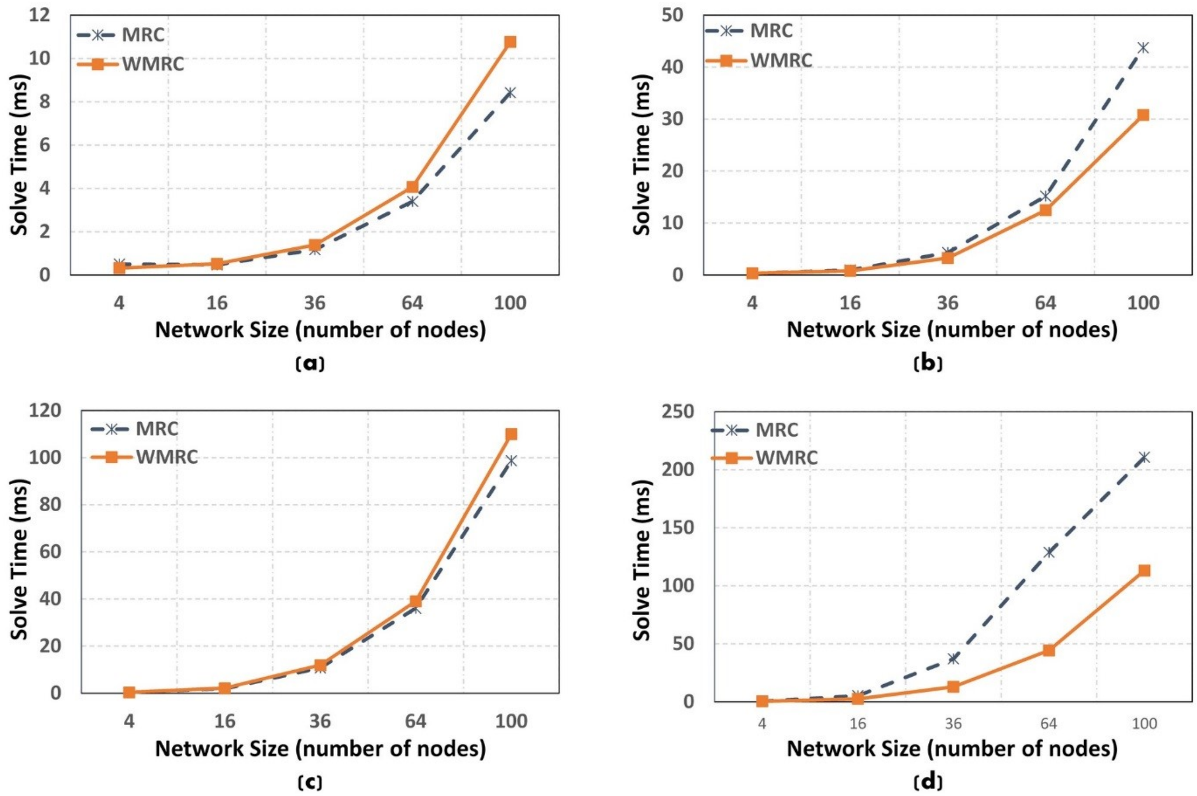

Figure 7: The solution time for the Maximum Residual Capacity (MRC) model and Wireless Maximum Residual Capacity (WMRC) model in grid topologies with various network sizes in the case a) One flow, b) Two concurrent flows, c) Three concurrent flows, and d) Four concurrent flows

Similar results regarding the power of CP solvers, supporting our findings, were also reported in (Hartert et al. 2015). The authors considered the use of CP programming to solve routing problems in traditional, non-SDN networks, and reported a multiple order of magnitude faster solve-time of the CP solver compared to an LP approach. In summary, SCOR's expressiveness and solving efficiency of complex QoS routing problems has shown very promising results in both aspects. We have implemented SCOR as a component on the POX SDN controller platform. More details on the implementation are available in our technical report (Layeghy et al. 2016).

8. Conclusion

The main contribution of this work is the introduction of a new northbound interface for SDN, based on constraint-programming techniques. The fundamental goal in the design of this northbound interface is to reduce the complexity of implementing QoS routing and TE applications in SDN, by providing an appropriate level of abstraction. SCOR, the proposed solution, provides the necessary building blocks, i.e. the predicates, to express complex routing problems in a very compact and simple manner, as we have demonstrated. A key aspect is the ease in which predicates can be combined, nested and reused.

A powerful aspect of SCOR, which it inherits from constraint programming, is the separation of the problem formulation and its solution. SCOR's layer of abstraction hides the complexity of the problem solution from the user, and therefore greatly simplifies the implementation of new routing and traffic engineering applications. The increased level of abstraction and simplicity does not at all come at a cost of reduced efficiency. Through the use of powerful generic constraint programming solvers, solutions to complex QoS routing problems can be found faster than through traditional procedural programming solutions, in some cases by orders of magnitude, as we have shown.

While we have focused on the application of SCOR for QoS routing and traffic engineering, we believe it has wider applicability, e.g. in security. We can envisage that security policies can be expressed as constraints in SCOR, and the guaranteed enforcement is delegated to the solver.

As mentioned, SCOR is currently implemented as a component in the POX controller. We are currently working on an implementation of SCOR in ONOS (Berde et al. 2014). We believe that SCOR adds a powerful and practical layer of abstraction to SDN, which greatly simplifies the problem of QoS routing, traffic engineering and possibly a range of other network applications.

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The Tragedy of Australia's National Broadband Network

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Abstract: This article reviews recent developments in global broadband deployments and highlights the growing global dominance of fibre to the premises (FTTP). Australia's increasing use of fibre to the node (FTTN) has locked the country out of world-class broadband for years to come. If Australia is ever to obtain first-class broadband services, it will be necessary to replace FTTN with higher speed technologies.

Keywords: Telecommunications; Broadband; Optical Communications; National Broadband Network

Introduction

Australia performs poorly in global rankings of broadband download speeds (Smith, 2017). NBN Co argues that the situation will improve (Dinham, 2017) as more customers connect to the fibre to the node (FTTN) and hybrid fibre coax (HFC) components of the National Broadband Network (NBN). However, this argument is valid only if Australian customers enjoy higher speeds than available on new broadband networks being rolled out elsewhere in the world.

This article reviews a number of recent developments in global broadband activities, highlighted at the 2017 Optical Fibre Communications Conference (OFC) and elsewhere, and shows how Australia's reliance on FTTN will ensure that broadband capabilities in Australia will continue to fall behind other developed and developing nations. I argue that to achieve world-class broadband Australia needs a longer-term plan to ensure there is a path to improving Australia's broadband infrastructure after completion of the NBN.

http://doi.org/10.18080/ajtde.v5n1.94

The 2017 Optical Fibre Communications Conference

In March this year, I attended the 2017 Optical Fibre Communications Conference (OFC), in Los Angeles. With a plan to glean as much information as possible about trends on broadband, I attended conference sessions on broadband and quizzed vendors and operators about developments in broadband access in North America, Europe, and Asia.

I wanted to find out more about global trends in broadband and to test NBN Co's suggestion (Dinham, 2017) that Australia will improve its place in broadband rankings as more customers connect to the NBN. What I found at OFC leads me to believe that Australia's position in the broadband rankings will slip even further as the rollout of FTTN across the NBN footprint continues.

Earlier this year, a report by Ovum (Ovum, 2017) showed that 2016 represented a global tipping point in broadband, with the number of fibre to the premises (FTTP) connections (almost 400 million) exceeding all copper (ADSL and FTTN) connections (300 million, in total). What's more, Ovum predicts that with continued rapid growth of FTTP deployments, this technology will deliver more than half of all broadband services by 2021. A separate report by wordpress (BroadbandTrends, 2017) comes to similar conclusions.

Lectures and panel sessions at OFC confirmed this analysis. Orange, for example, is planning a rapid ramp-up of FTTP in Spain and France over the next few years. Similar trends are happening in other European and Asian countries. In a presentation I made about broadband, I showed data from a Point Topic study (Point Topic, 2017) indicating that globally, FTTP connections increased by 77% in 2016 and copper connections (including FTTN) decreased by 11% of total deployments.

While there has been a large increase in FTTP globally, Google Fiber, in the USA, has slowed their rollout of FTTP for a variety of reasons, including problems around installing fibre on power poles used by competitors – the so-called one touch make ready laws (Kennedy, 2016). On the other hand, network operators such as Verizon and AT&T are taking up some of the FTTP slack left by Google.

Importantly, a plethora of public-private partnerships involving companies and local government are also rolling out FTTP across the USA. Local governments are often well aware of the economic benefits of good broadband to their communities and have been very effective in attracting broadband investments. In these networks, a city often owns the fibre, and provides various incentives to network operators to participate. City-focused initiatives of this kind have led to more than 5000 FTTP providers in the USA.

Fibre to the Node and Fibre to the Curb

Australia is one of only a few countries to opt for mass deployments of FTTN. Others include the UK, Germany, Austria and Greece. In defending its choice of FTTN technology, NBN Co often points to the UK and Germany as examples of where FTTN services exist. However, according to studies by New Street Research (New Street Research, 2017), BT, the incumbent operator in the UK and Proximus in Belgium both plan to move away from FTTN and replace at least some of the existing FTTN infrastructure with FTTP and fibre to the curb (FTTC).

In the UK, 91% of broadband customers in the UK currently use FTTN, but by 2022, FTTN will account for only 47% of broadband connections, while fibre to the curb/distribution point (FTTC/dp) and FTTP will provide 51% of broadband services. With Belgium and the UK moving away from FTTN, Australia (and Germany) will be further isolated from the mainstream of broadband technologies.

In the USA, AT&T rolled out about 30 million FTTN connections up 2015, and then moved to FTTP for most new deployments. AT&T expects to have 14 million residential and business customers connected to FTTP by the end of 2019 (Breznick, 2016).

The US operator Verizon originally provided some FTTN services. But there were many customer complaints and reliability issues with these early FTTN deployments. Verizon solved these problems by replacing FTTN with FTTP. To quote a Verizon speaker at OFC: "What you deploy stays in the network for a long time. Therefore, it is important to think long-term and deploy technology that meets long-term needs".

Verizon says that their customers are demanding 40% to 60% more bandwidth each year. This contrasts somewhat with NBN Co's statements that suggest Australians do not want higher bandwidths (Osman, 2017). But who can blame Australian customers for being wary of an FTTN network that is gaining a bad reputation in the press through mounting anecdotal evidence of poor performance (Manning, 2017) and when, at the same time, NBN Co is talking down the need for bandwidth?

Verizon admitted that they made mistakes in their early deployments of FTTN and BPON (an early FTTP technology). Today they choose a platform that will be useful for 10 – 15 years, with a clear path to greater than 10 Gigabit per second capability.

There has been some recent discussion as to whether FTTC would be an appropriate alternative to FTTN in Australia. Asked at OFC about whether they have considered FTTC for future deployments, Verizon said that because of their earlier bad experiences with FTTN they have decided not to roll out FTTC. This could be a wise choice for now. No large-scale deployments have been undertaken and questions remain about its reliability and operational costs.

Gigabit per Second Services

Google Fiber's move into broadband delivery in 2011 was a game changer in the US broadband market. Google's gigabit per second offerings stimulated AT&T to offer gigabit per second services. AT&T now is planning to offer gigabit per second services to its 14 million FTTP customers by 2019.

Today, there are more than 250 "gigabit cities" in the USA (Cities with Gigabit Internet), in which gigabit per second services are available over FTTP. There is growing evidence that gigabit cities enjoy economic advantages over cities without very-high-speed Internet access. See, for example (Richards, 2016) and (Fisher, 2016).

A number of cable (HFC) companies in the US are offering gigabit per second services over HFC by upgrading to DOCSIS 3.1. Other cable companies have decided to roll out FTTP rather than upgrade to DOCSIS 3.1. In Australia, NBN Co is upgrading Telstra's HFC network to DOCSIS 3.1.

A China Telecom speaker pointed out at OFC that China Telecom is targeting 100 Mb/s minimum for all broadband users by 2020 with gigabit per second services planned to be available in most cities by 2020.

Upgrade paths

One Panel Session at OFC featured a discussion of upgrade paths for FTTP networks. Coming from Australia, I naively expected this discussion to address whether FTTN or FTTC might be suitable interim technologies for use in the years before a full FTTP deployment.

But I was wrong. Because the world has moved on from FTTN, which is rapidly becoming obsolete, the discussions were, in fact, about how to upgrade FTTP networks from today's gigabit passive optical network (PON) technology to more advanced FTTP technologies such as XGSPON and NGPON2.

To help explain possible upgrade paths, Fig. 1 shows the growth of commercial fibre and copper broadband technologies from 1994 to 2019. The vertical axis is the achievable maximum download speed, and the horizontal axis represents the year that each technology was standardized and/or became commercially available, or is expected to become available on the market.

The upper group of technologies are flavours of passive optical network (PON), delivering FTTP. The lower groups are different copper and fibre/copper technologies, namely ADSL, FTTN, and fibre to the distribution point or curb (FTTdp/C). Not explicitly shown on the figure is that the speed of the PON technologies are independent of distance, while the speeds of the copper-based technologies are strongly dependent on distance.

Most FTTP deployments around the world, including the NBN, use GPON. The newer technologies such as 10GPON, XGPON, XGSPON and NGPON2 offer maximum speeds of up to 10 gigabits per second and beyond.

In the future 100GPON will operate at an impressive 100 gigabits per second. Of course, not every customer will want or need 10 - 100 gigabits per second. But, importantly, XGSPON and NGPON2 networks can be overlaid on existing GPON networks.

In other words, existing GPON customers with gigabit per second or slower services are unaffected by the higher speed services on the network, and vice versa. Those customers enjoying multi-gigabit-per-second services using newer technologies can hook onto the existing fibre infrastructure with little or no upgrade of the physical fibre infrastructure.

This means that a small business requiring a higher speed service than a residential customer will be able to access the bandwidth it needs, while nearby residential customers can receive services at an appropriate speed for their requirements.

Some supporters of the FTTN network argue that businesses and high-end users have the ability to access FTTP using NBN Co's so-called technology choice program (Technology Choice Program, 2016). However, the costs of converting to FTTP under this program are unknown, and potentially high, making it very unattractive to small businesses, especially those operating from rented premises.

This aspect of flexibility of access was one of the promises of the original FTTP-based NBN in Australia. However, in what has become a narrowly confined debate about Australia's NBN, this important point seems to have been lost.

At OFC, a number of operators talked about how they are planning to upgrade their GPON networks to XGSPON and NGPON2. There is some debate about whether XGSPON should come before NGPON2 due to the need for tuneable lasers. However, China Telecom is aggressively targeting NGPON2, while Orange, AT&T, and Verizon are planning to offer upgrades to XGSPON.

Orange will start offering XGSPON in Spain and France from 2018 to 2020, enabling customers to choose to receive multi-gigabit per second services.

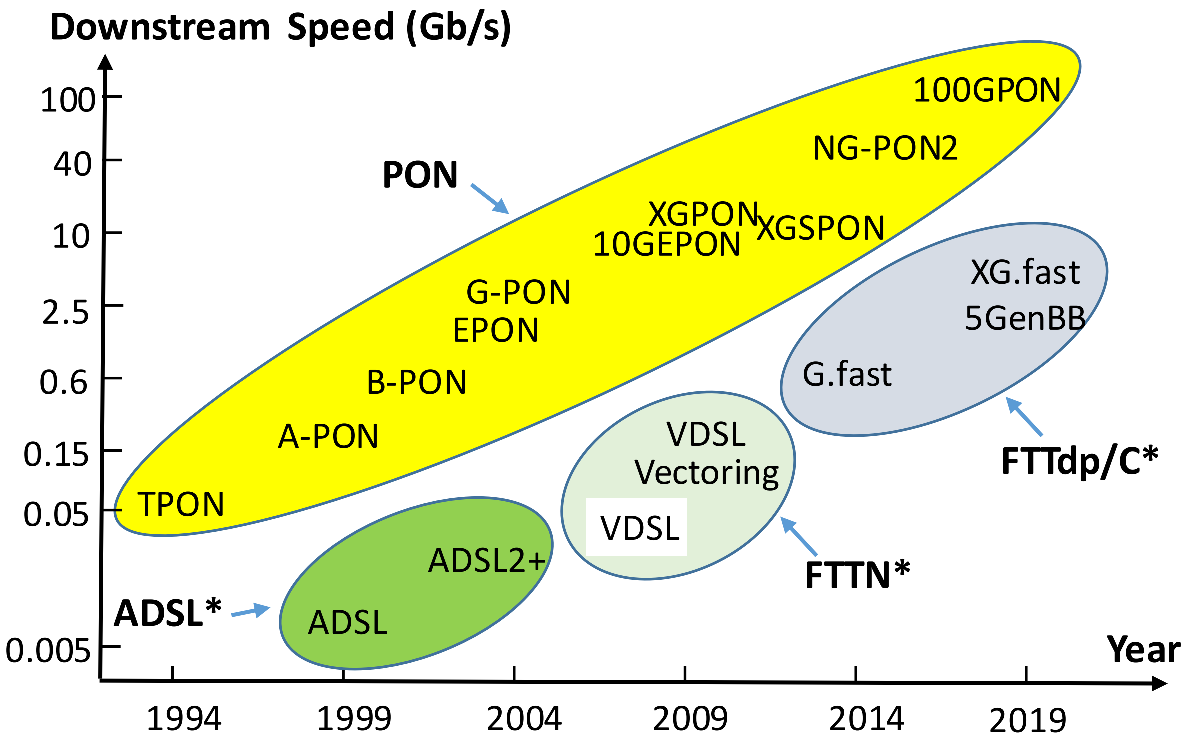
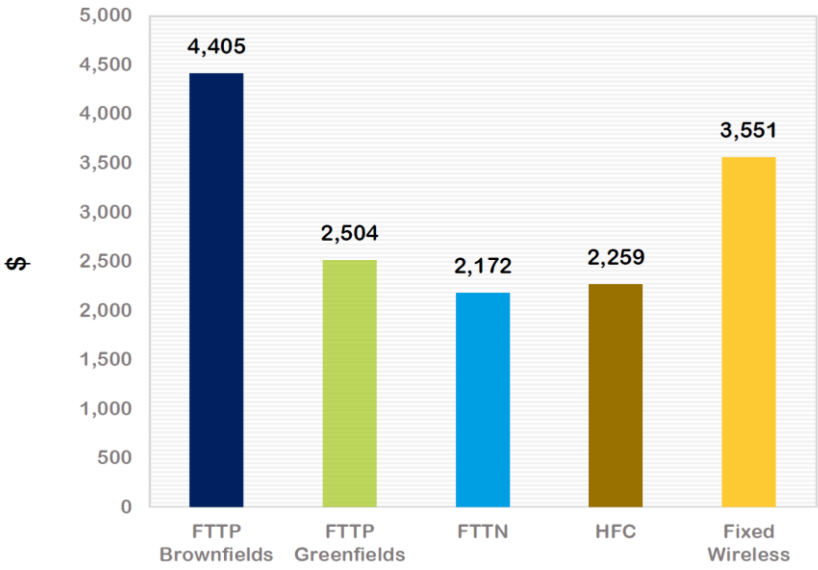


Fig 1. Evolution of PON, DSL, FTTN(VDSL) and FTTdp standards over time, showing download bandwidth achievable with each standard. (Effenberger, 2016)

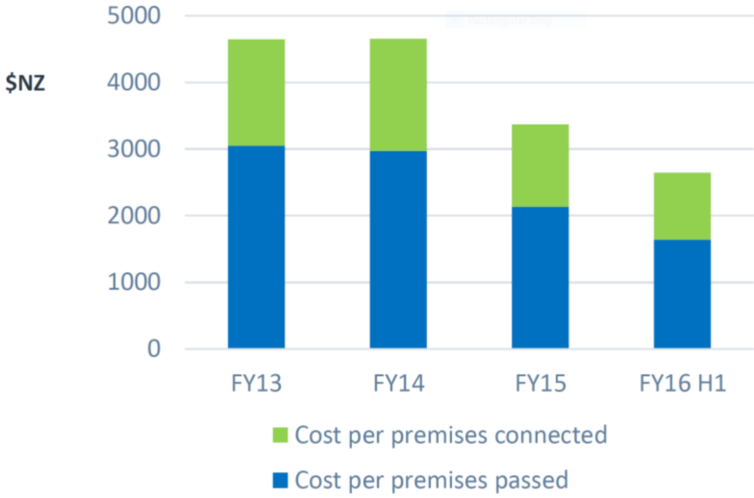
Fibre Deployment Costs

I went to OFC hoping to find out more about the deployment costs of FTTP. NBN Co repeatedly argues that FTTP is too expensive for Australia when defending their decision to deploy FTTN rather than FTTP. This assertion needs to be tested.

Fig. 2(a) shows NBN Co's deployment costs per premises for all of the technologies in the multi-technology mix (MTM), except for FTTC. The average cost per premises of FTTP is $4405, including the fibre connection into the home, while NBN Co's average cost for FTTN is $2172 per premises.



(a)



(b)

Fig. 2 (a) NBN Co's average costs of each NBN technology per premises connected. (NBN 2017 half year results, 2017) (b) Chorus' average costs for FTTP. (Chorus, 2016)

In attempting to validate these numbers against international benchmarks, I found many operators unwilling to disclose publicly their FTTP deployment costs. However, all operators that spoke at OFC have made it clear that FTTP deployment costs have been reduced by at least 5 – 10 % every year through improved construction practices such as field-installed connectors, skinny fibre and micro-trenching, workforce training, improved location-dependent task management and newer technologies. As an example, Verizon has reduced the cost of deploying FTTP by 50% since they started rolling out FTTP.

In New Zealand, Chorus has decreased the deployment cost of FTTP by 44%. Fig. 2(b) shows Chorus' costs for deploying FTTP, indicating that they have reduced the cost of deployment from about NZ$4400 in 2013 to about NZ$2800 in 2016. This latter figure is almost the same as NBN's costs for FTTN. No wonder Chorus decided to move from FTTN to FTTP – the opposite to what NBN has done.

Google Fiber have not disclosed their costs for FTTP, but they pointed out at OFC that rolling out FTTP is possibly less expensive than upgrading and existing network to DOCSIS 3.1

If NBN Co's estimates of upgrading to DOCSIS3.1 are correct, Fig. 2(a) suggests that Google's cost per premises for 1 gigabit per second FTTP may be less than NBN Co's cost estimate for FTTN and certainly less than NBN Co's claimed costs for FTTP.

NBN Co seems unwilling to admit that their claimed cost of $4405 for FTTP costs is too high by today's international standards. Yet in a recent statement about FTTC (Keisler, 2017), NBN Co argued that newer construction methods such as skinny fibre could reduce the cost of future upgrades of FTTN to FTTC. But NBN Co makes no mention of how these same methods can be used to reduce the cost of FTTP.

A National Tragedy

Australia's National Broadband Network is heavily dependent on a soon-to-be-obsolete technology (FTTN) that most of the world has rejected. The FTTN-based network was sold to the Australian public based on an underestimate of Australia's broadband needs (Tucker, 2014), and continues to be justified using incorrect estimates of the cost differentials between FTTN and FTTP.

The FTTN network performs poorly compared to FTTP networks used elsewhere in the world. What is worse is that the NBN does not have a clear and affordable upgrade path. FTTN is of limited value to some users, such as high-end users and small businesses, who require affordable access to higher speeds than FTTN can deliver.

In the meantime, the rest of the world is moving to FTTP and gigabit cities are thriving. Leaders in broadband delivery around the world are already planning for upgrades in their FTTP technology to even higher speeds.

This situation is nothing short of a national tragedy and a classic example of failed infrastructure policy that will have long-term ramifications for Australia's digital economy.

The Way Forward

There is now a growing concern that it is going to be hard to fix this diabolical problem. NBN has made it clear that it is too late to make another change (Keisler, 2017). According to Mike Quigley, critic of the MTM and a former CEO of NBN Co, "There now is no practical way to turn back the clock and recoup all of the money that is being spent on the MTM." (Varghhese, 2017)

So how do we dig ourselves out of this hole?

There are no easy answers, but it is time to start planning for a future beyond the NBN completion date of 2021. One strategy might be to draw on grass-roots activities at the city and town level. In the USA, local government has been very successful in facilitating FTTP initiatives and promoting gigabit cities.

Conclusions

It is difficult to find a positive note on which to conclude this article. However, one thing is certain – the demand for broadband will grow, and new and innovative service and application platforms will drive the digital economy. At some point in time, Australia's broadband infrastructure will have to move into the 21st century.

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