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Debating Wholesale Telecommunications Reforms

Editorial

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Abstract: Papers in the June 2018 issue of the *Journal* cover what to do with the National Broadband Network when the rollout is completed, Unmanned Aerial Vehicle communications, energy efficient mobile ad-hoc network communications and a historical look at the Black Mountain Tower in Canberra. With the completion of the National Broadband Network rollout in coming years, there will be an opportunity for substantive wholesale telecommunications reforms to occur that will shape the telecommunications industry for decades to come. Central to this debate is the future of the National Broadband Network: it is important that this debate commence now, so that there will be time to explore the options and for the telecommunications industry, government, business and consumers to come to a consensus on what should happen next and what the expected outcomes of the wholesale telecommunications reforms should be. The *Journal* welcomes contributions.

In This Issue

In this issue, the *Journal* includes topical articles that cover what to do with the National Broadband Network (NBN) when the rollout is completed, Unmanned Aerial Vehicle communications, energy efficient mobile ad-hoc network communications and a historical look at the Black Mountain Tower in Canberra.

Data Transfer via UAV Swarm Behaviours presents an adaptive robotic swarm of Unmanned Aerial Vehicles (UAVs) enabling communications between separated non-swarm devices.

An Energy Efficient Receiver-based Flooding Scheme Using 1-Hop Neighbours Geographical Information for MANETs proposes an efficient flooding protocol that minimizes flooding traffic, leveraging location information of 1-hop neighbour nodes.

Australian Wholesale Telecommunications Reforms considers what the government of the day should do with the NBN after the NBN is built and fully operational in 2022.

Black Mountain Tower Canberra provides two historic papers from a special issue of the *Journal* in 1981 featuring the new Black Mountain telecommunications tower in Canberra.

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What should the future be for the National Broadband Network?

This month the *Journal* includes a paper that aims to start the debate about what should be done with the NBN when it is completed in 2022. This is a debate that we need to have for a number of reasons, chief among them being the need for the telecommunications industry, government, business and consumers to find common ground that moves the telecommunications deregulation process forward and not backwards.

Australia needs a telecommunications industry that is open, fair and competitive and one that provides world's best telecommunications to every Australian, irrespective of where they live or work.

It is time for the digital divide to become a thing of the past, but this will only occur when regional and remote Australians are provided with telecommunications that compares favourably with the telecommunications provided to those living in urban areas.

It is also time for every Australian to be provided with universal access telecommunications to ensure that health, education and other government-provided digital services can be accessed by everyone, irrespective of their means and where they live or work.

The NBN is more than telecommunications infrastructure, it is the foundation on which much of this nation's future will be built. The next decade will bring about unprecedented change to how we use telecommunications in our daily lives, just as the last decade saw the introduction of smart phones, tablets, video streaming services, etc.

It is time for the future of the NBN to be debated. The decision about the future of the NBN should not be left until the last moment, as this might mean that the government of the day could make the decision based on ideology or a short-term fiscal outcome, rather than what is best for the nation in coming decades.

The *Journal* welcomes papers on the future of the NBN, wholesale telecommunications reform and telecommunications deregulation.

The *Journal*, Looking Forward

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

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

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

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

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Australian Wholesale Telecommunications Reforms

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Abstract: The Australian telecommunications market has been reshaped with the introduction of the National Broadband Network (NBN), arguably a short-term renationalisation of the fixed-access telecommunications infrastructure. The NBN rollout commenced in 2009 and is expected to be completed by 2021. The telecommunications market has evolved rapidly as the NBN has taken shape and it is anticipated that the telecommunications industry will seek a period of certainty following the NBN's completion. This paper considers what the government of the day should do with the NBN after the NBN is built and fully operational in 2022. It discusses four options for the ownership of NBN Co beyond 2022 and describes arguments for and against each option. Telecommunications provides an essential service, is central to the nation's participation in the global digital economy, and the management of telecommunications infrastructure is a national priority.

Keywords: Telecommunications, Wholesale, National Broadband Network, Policy, Regulation

Introduction

This paper investigates whether there is a need for further telecommunications market reforms to coincide with the completion of the Australian Government initiative to roll out a National Broadband Network (NBN) (DCA, 2018b).

There are a range of options for how the telecommunications market reforms might occur and the potential benefits vary depending on the weight given to various factors, including what's best for the nation, long-term interest of end users, infrastructure security, market value and future competition.

Telecommunications market reforms should provide an opportunity to remove impediments to a fair, open and competitive telecommunications market whilst providing outcomes that are in the long-term interests of end users.

A fair, open and competitive telecommunications market can be elusive and hard to achieve depending on a range of factors including the political, social and economic circumstances at the time that a nation embarks on a process of telecommunications market reform.

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Telecommunications is an essential service, and telecommunications infrastructure is a national asset that fulfils a vital role, providing telecommunications services that underpin the economy, emergency response, government, business, industry and national security.

The Australian telecommunications market has been subjected to specific policies that are highly contentious and grounded in neo-liberalism, resulting in widely discredited conceptual policy frameworks (Gregory, 2014b). The chaotic telecommunications legislative and regulatory environment is a result of ideology-driven political intervention, the result of which has been a lack of certainty for the telecommunications industry and consumers (ABC, 2014; Durie, 2017; Penn, 2017; Biddington, 2018).

Telecommunications Deregulation

For many nations the telecommunications deregulation process commenced 25 years or more ago, when government-owned telecommunications providers were wholly or partially sold off and privatised telecommunications markets were created. This process was not uniform and the result was a global mix of privatised telecommunications markets struggling with aspects of their unique formulation (Kautsarina, 2017; Hansen, 2017; Middleton, 2017; McLaren, 2017; Saenz De Miera, 2017; McDonough, 2017).

Governments introduced legislation and regulation to support the formation of new telecommunications markets that were intended to provide a fair, open and competitive landscape into which new and existing companies could invest, build networks and grow market share.

To support the new relationship between the government, telecommunications industry and consumers, key regulatory, dispute-resolution and industry bodies were either put in place or enhanced to provide the necessary glue and balance between the parties in this new telecommunications environment.

The government department responsible for telecommunications interacts with the regulatory bodies, state and local government and other organisations, including consumer groups, to formulate legislation and regulations (DCA, 2018a).

Two independent statutory bodies in Australia provide an umbrella under which the telecommunications industry operates. The Australian Competition and Consumer Commission (ACCC) is responsible for competition and consumer protection (ACCC, 2018a) and the Australian Communications and Media Authority (ACMA) is responsible for the technical operations, including technical standards, codes of practice, spectrum management, industry operations levies, rules and public-interest activities (ACMA, 2018).

Key points of interaction with the telecommunications industry are provided by two bodies. The first is an independent telecommunications industry ombudsman formed as a public company that is funded by its industry members to handle consumer complaints categorised in its charter, with powers to impose fines on members and compensate consumers under the enabling legislation (TIO, 2018).

The second is an industry body formed to provide a point of contact, forum, codes of practice and self-regulatory initiatives (CA, 2018). The Australian telecommunications industry body, Communications Alliance, "was formed to provide a unified voice for the Australian communications industry and to lead it into the next generation of converging networks, technologies and services" (CA, 2018).

Due to the membership, financial contribution and voting rules, industry bodies may fragment at times when there is a perceived need to highlight issues or industry segments. Over the past decade, additional Australian telecommunications industry bodies and lobby groups have been formed, including the Competitive Carriers Coalition (CCC) (CCC, 2018) and the Australian Mobile Telecommunications Association (AMTA, 2018).

The CCC states on its website that "communications competition in Australia appears to be stagnating, leaving consumers with internationally uncompetitive prices and services. This requires the Federal Government to review the adequacy of policy in a post NBN, post convergence world, and the ACCC to take a strong line in addressing prices that remain out of line with international benchmarks" (CCC, 2018).

The AMTA states that it "is the peak industry body representing Australia's mobile telecommunications industry. AMTA members include mobile Carriage Service Providers (CSPs), handset manufacturers, retail outlets, network equipment suppliers and other suppliers to the industry" (AMTA, 2018).

The telecommunications deregulation process is ongoing and the interaction between government, the industry and consumers can be dynamic, as governments introduce, amend and repeal legislation and regulation depending on their ideology, feedback from the industry and consumers and as a result of input from expert panels, committees and reviews (TLADB, 2014).

Telecommunications deregulation has provided a fertile area for research and opinion that provides a valuable insight into the understanding of the process at the time (McCormick, 1996) and the outcomes, including how deregulation affects the labour market (Batt, 1998).

Argument that deregulation is a panacea for reducing costs and increasing competition is ongoing, substantial and can, at times, be undermined by the industry that is supposed to

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benefit from the deregulation process due to the non-homogeneity of direction taken by companies that make up the industry.

The conclusions put forward by Hausman and Taylor (Hausman, 2012), in their analysis of Kahn's seminal works on regulation and deregulation, including *The Economics of Regulation* (Kahn, 1988), *Lessons from Deregulation* (Kahn, 2004), *Network Neutrality* (Kahn, 2007), include:

- "prices must be informed by costs; costs are actual incremental costs; costs and prices are an outcome of a Schumpeterian competitive process, not the starting point; excluding incumbents from markets is fundamentally anticompetitive.
- a regulatory transition to deregulation entails propensities to micromanage the process to generate preferred outcomes, visible competitors and expedient price reductions.
- where effective competition takes place among platforms characterized by sunk investment—land-line telephony, cable and wireless—traditional regulation is unnecessary and likely to be anticompetitive."

Kahn reached a conclusion that different industries require different mixes of institutional arrangements that cannot be decided on the basis of ideology (Kahn, 1988). Kahn's body of work and the conclusions reached by Hausman and Taylor reflect much of the economic argument regarding deregulation put forward over the past thirty years, and is applicable to most industries. As pointed out by Kahn, where effective competition does not take place among platforms characterized by sunk investment, regulation is necessary.

The regulator may regulate telecommunication products and services because of the prohibitive cost of infrastructure, competitive access to infrastructure, providing products and services into areas of low customer density, new technologies, a dominant market participant and other factors.

As an example, the Australian NBN partially originated because of Telstra's refusal to upgrade the fixed-line network (Gregory, 2017) after putting a complex and expensive plan to government that resulted in a Government demand that potential support would be contingent upon Telstra agreeing to horizontal structural separation.

Telstra, the incumbent telecommunications company, argued that fixed-line infrastructure investment would benefit its competitors and undermine Telstra's position due to the potential for the new infrastructure to be regulated in terms of price and access (Hogan, 2006; AAP, 2007; Dodson, 2005; Bartholomeusz, 2006).

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Telstra's assessment was correct, but it was in the position it found itself due to a Government failure early in the deregulation process to identify the future problems associated with a single company owning most of the fixed-line infrastructure and facilities.

After the Howard Government had failed to resolve the impasse with Telstra, the Rudd Government decided to create a government business enterprise (GBE) to build a new wholesale fixed-line access network, effectively renationalising fixed-line telecommunications to residential and small business premises.

Australia's telecommunications deregulation journey has taken more than 25 years. It is arguable that, until the NBN is built and fully operational, the telecommunications deregulation process will be ongoing. Telecommunications, as an essential service, will always remain a regulated market because of its nature and market structure, although the nature and intensity of regulation will inevitably change in future, as it has in the past 25 years.

As the deregulation process occurs there is a need to constantly review how a fair, open and competitive telecommunications market will be achieved whilst providing outcomes that are in the long-term interests of the nation and end users.

The Australian telecommunications Universal Service Obligation (USO) (USO, 2018) is one example of government intervention related to fairness and equality of access. Government intervention programs related to fairness and the national interest have evolved to meet new circumstances such as the current and ongoing need to provide universal access to telecommunications and digital services (Gregory, 2015a).

NBN Completion Date

NBN Co updates its rollout planned availability dates in response to a range of factors associated with the multi-technology mix approach adopted after the September 2013 Federal election. Key amongst the factors has been the remediation cost of the Hybrid Fibre Coax (HFC) networks purchased by NBN Co from Telstra and Optus and the remediation cost of the copper to be used in the Fibre-to-the-Node (FTTN) networks. The decision to add Fibre to the Curb (FTTC) to the multi-technology mix solution has meant that some areas previously zoned to receive HFC and FTTN have been rezoned as FTTC. NBN Co rollout and planned availability of service now extends into mid-2020.

The Migration Assurance Framework – Telecommunications Industry Guide (MAF, 2017) states that "once nbn declares an area to be Ready For Service (RFS), customers, whether households or businesses generally have 18 months to migrate their voice, broadband and over the top services to the NBN or alternative telecommunications network. This 18 month period is known as the migration window".

The migration window was originally linked to the Subscriber Agreement section of the binding definitive agreement between NBN Co and Telstra signed on 23 June 2011 (NBNCO, 2011). A summary stated:

> "In broad terms, the disconnection [of the legacy access network excluding Pay TV services] must be completed within 18 months of NBN Co declaring that rollout region to be ready for service (which cannot happen until at least 90% of the premises in that rollout region are passed by NBN Co fibre). A separate regime (with a different time frame for disconnection) applies to disconnection of special services provided over the copper Customer Access Network. Disconnection protocols have been agreed to govern this."

A key change in the revised Definitive Agreements signed by NBN Co and Telstra on 14 December 2014 (Turnbull, 2014a) was to the section affecting the copper and HFC networks: (Telstra, 2014)

> "Original DAs (June 2011) - Disconnected 18 months after an area is declared Ready for Service by NBN Co.
>
> Revised DAs (Dec 2014) – Rollout regions with FTTP, FTTN and/or HFC deployment:
>
>> Disconnected 18 months after an area is declared Ready for Service by NBN Co.
>>
>> Ownership of relevant copper and HFC assets progressively transferred to NBN Co such that it owns them as at the Ready for Service date."

Under the revised Definitive Agreements, Telstra and Optus would progressively transfer ownership and maintenance of the copper and HFC networks to NBN Co as the NBN rollout occurs in each area.

The Migration Assurance Framework statement that "households or businesses generally have 18 months to migrate their voice, broadband and over the top services to the NBN or alternative telecommunications network" appears to uphold the original principle that customers would have a window of opportunity to transition to the NBN.

The NBN will not be built and fully operational until early 2022 based on the latest rollout planned availability and migration window. To argue that the NBN is built and fully operational when the last rollout area is deemed "ready for service" (or using NBN Co's most recent variation "ready to connect") before the end of the migration window in all rollout areas and before the legacy network disconnection has occurred, is not justifiable. The NBN build, including customer premises broadband connections, legacy equipment connections and remediation associated with connection problems identified when customers move to the NBN, that would be expected to occur as a result of the NBN rollout and first use of a connection during the migration window, may not have been completed. Also, the VDSL2 equipment used for the FTTN connections cannot be switched over to vectoring mode until the legacy network disconnection has occurred. The NBN is therefore not fully operational until the migration window is closed.

NBN Sale Requirements

According to the *National Broadband Network Companies Act 2011*, the NBN can be sold when (NBN, 2011; DCA, 2018b):

- "the Minister for Communications declares that the nbn is built and fully operational;
- the Productivity Commission has an inquiry into regulatory, budgetary, consumer and competition matters relating to the nbn;
- a Parliamentary Joint Committee considers the findings of that report;
- the Minister for Finance makes a disallowable declaration that conditions are suitable to sell nbn; and
- Parliament doesn't disallow that declaration."

The NBN sale requirements include the requirement for a Productivity Commission inquiry that would be anticipated to take 12 months based on the similarly scoped Productivity Commission Inquiry into the Telecommunications Universal Service Obligation (PC, 2017).

A consideration for the NBN sale is the "off budget" Government peak funding of $48.7 billion that is broken into two components: equity funding of $29.5 billion; and debt funding of $19.2 billion (NBNCO, 2017). It is possible that one or more of the options discussed in this paper might require that the Government's contribution to NBN Co be brought "on-budget" or partially or wholly written off.

The final NBN sale requirement indicates that, for the NBN sale to proceed, approval from both Houses of Parliament is required, potentially slowing or halting a Government-initiated sale process.

Customer Connections

In response to a question with notice (number 175) (SECEC, 2017a) at the Senate Estimates Committee on the Environment and Communications, NBN Co stated on 12 January 2018 that the "estimated proportion (%) of premises who can access layer 2 speed of 100 Mbps or more by rollout completion" was:

- FTTP – 100%

- FTTN – 24%
- FTTB (Fibre to the Building) – 100%
- FTTC – 100%
- HFC – 100%
- Fixed Wireless – 50%
- Satellite – 0%

On 24 May 2018, at a Senate Estimates Committee hearing, NBN Co CEO Bill Morrow indicated that the fixed wireless 100 Mbps speed product was withdrawn (SECEC, 2018).

The NBN Co Corporate Plan 2018-2021 (NBNCO, 2017) states that, in FY21 (1 July 2020—30 June 2021), 11.7 million premises will be ready for service with:

- FTTP Brownfields – 1.2 million;
- FTTP Greenfields – 0.8 million;
- FTTN/B – 4.6 million;
- FTTC – 1.0 million;
- HFC – 3.1 million;
- Fixed Wireless – 0.6 million;
- Satellite – 0.4 million.

On 10 April 2018, NBN Co announced (NBNCO, 2018a) that the FTTC footprint would increase by an additional 440,000 premises. The media release stated that "these premises are inside or adjacent to existing Telstra HFC network coverage but are not able to connect to the Telstra HFC network". NBN Co CEO Bill Morrow stated that "we are also excited to announce we will be expanding FTTC to cover an additional 440,000 in areas where some long-copper FTTN and new HFC lead-ins were previously planned."

Telstra

NBN Co and Telstra are inextricably linked because of NBN Co's genesis and the annual, leasing payments that NBN Co makes to Telstra to utilise Telstra's infrastructure and facilities. Mr Morrow and NBN Co Chief Financial Officer, Stephen Rue, revealed the leasing arrangement cost of $15 per customer per month at a Senate estimates hearing on 24 October 2017 (SECEC, 2017b).

In 2016, ratings agency Moody's indicated that Telstra would struggle to fill a $2-3 billion earnings gap when the NBN is built and fully operational. Moody's estimated that Telstra's ongoing loss of revenue from its wholesale business would be about $700 million per annum. Telstra would also have to pay NBN Co for wholesale access to customers, further eroding pre-tax profits (ABC, 2016a).

In 2012, Telecom NZ split into Spark (retail) and Chorus (wholesale). Spark and Chorus have found their feet since the split and are performing well. Spark and Chorus have a focus and, as smaller businesses, they have become more agile and able to compete in New Zealand's rapidly changing telecommunications market.

Spark's share price today (June 2018) is $3.25 after falling to $1.50 in late 2011 when Chorus was split off. In late 2011, Chorus was at $2.53 and, after a period of consolidation, investment and growth, it is now at $3.76.

Over the same period, Telstra's share price has risen from $3.12 in late 2011 to $6.59 in February 2015 and fallen back to $2.87 on 15 May 2018.

On 28 May 2018, Telstra's long-term rating was downgraded by Standard and Poor's from A to A-, with the short-term rating falling from A-1 to A-2 (ABC, 2018).

A 2012 decision by the Australian Competition and Consumer Commission (ACCC) (ACCC, 2018) to increase the number of Points of Interconnect (PoI) to the NBN to 121, from NBN Co's proposed 14, meant that the existing transit networks, including Telstra's extensive transit network, became a factor in the overall cost of access to consumers.

To alleviate this situation the Government rolled out additional transit links in areas where Telstra was the only transit link provider and the ACCC carried out a domestic transmission capacity service declaration inquiry that resulted in some of the transit links being price regulated (ACCC, 2014a). The current declaration extends to 31 March 2019. It is not anticipated that there would be a major change to the status quo resulting from the 2019 review.

For Telstra, the decision by the Abbott Government in September 2013 to adopt the multi-technology mix NBN plan has made the future more complicated because the homogenous reliable, high speed and high capacity all-fibre NBN is not available as a platform upon which Telstra can provide new and innovative digital products and services (Gregory, 2012).

Telstra's foreign ownership restrictions are likely to come under scrutiny as part of any sale of the NBN. By 2022, the NBN will be built and fully operational and, if the Turnbull Government wins the next Federal election (due by May 2019), there is likely to be a replacement program for the Universal Service Obligation (USO, 2018; PC, 2017), removing the concept that Telstra

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is the "service provider of last resort". The foreign ownership restrictions that apply to Telstra state that "no more than 35% of its shares may be held by foreign entities and no more than 5% by any single foreign entity" (Lattey, 2017, p. 14).

Telstra resisted upgrading its access network infrastructure for more than a decade between 1996 and 2007 and has continued until recently (see Endnote) to resist splitting the company into two companies, one retail and one wholesale (Gerrand, 2004; Gerrand, 2017; Gregory, 2014a; Gregory, 2014b; Gregory, 2018a).

Wholesale Reform

The future of the NBN after it is built and fully operational is central to the formation of an Australian wholesale telecommunications reform package designed to provide the telecommunications industry with certainty in the decades to come.

With the advent of the NBN, there has been increased competition (about 180 service providers (Duke, 2017)) and disruption in the retail telecommunications market that has motivated the retail service providers, led by Telstra (Smith, 2017b), to begin the process to move beyond handsets and bitstream.

A key shift has occurred in the telecommunications market, the advent of "unlimited" broadband plans. The increased competition in the fixed and mobile retail broadband markets has increased the pace at which service providers have had to decrease margins and increase monthly data usage allowances.

The disruption caused by the NBN should not be underestimated. Telstra's market size has been reduced and it is having to transform to reposition itself, to retain market share and to offer new products and services.

Australia needs a telecommunications market where we do not see a repeat of the missteps that occurred during earlier telecommunications deregulation. Foremost, we do not need a telecommunications industry that relies on handsets and bitstream for survival. The future should be based on over-the-top products and services, and we need the telecommunications industry to be focused on providing Australians with access to new and innovative products and services.

Arguably, by 2022, for the first time, every Australian will enjoy reasonable access to broadband, albeit with differing levels of reliability and performance, but the end of the NBN rollout may see the momentum for continued investment and innovation falter.

Telecommunications is an essential service and, therefore, telecommunications infrastructure is not something that should be allowed to become obsolete (Gregory, 2017b).

The nation's future in the global digital economy must be secure. Australia was ranked 60 in the world for broadband speed in 2016 (ABC, 2016b), a drop from position 25 a decade earlier. For an industrialised country that likes to think that it is an early adopter of new technologies, Australia has struggled to retain a reasonable position in the world broadband rankings, due to the delay to move beyond ADSL during the 2000s and the decision to adopt the multi-technology mix in 2013 (Gregory, 2016a; Gregory, 2017).

NBN Co is a wholesale telecommunications products and services provider. Absent effective regulation, NBN Co could unreasonably use its market position to set unfair and exorbitant prices and adopt unfair and restrictive practices. Effective regulation, in this context, relies upon the government and the ACCC to work in concert to ensure that NBN Co is subject to fair and open infrastructure competition, that competitors are required to offer wholesale access to infrastructure, that uniform national wholesale pricing is maintained by wholesalers, with each wholesaler permitted to set different uniform national wholesale pricing, and removal of barriers to becoming an infrastructure wholesaler.

It is possible that the ACCC's position on some aspect of NBN Co's operation may not be in concert with the position of the service providers and, as seen with NBN Co's pricing model changes, there can be a need for re-evaluation of decisions taken by NBN Co or the ACCC. For example, NBN Co product pricing that undermines the principle of uniform national wholesale pricing should be opposed by the ACCC or, if necessary, enforced through regulation by the government.

Uniform national wholesale pricing is a principle that should be enforced to ensure that regional and remote consumers are not disadvantaged. Wholesalers can still compete effectively, if wholesalers offering products in regional and remote areas can receive funds for each connection from the regional and remote broadband levy.

As a wholesale telecommunications product and services provider, NBN Co's potentially dominant position can be tempered by removing existing legislative restrictions on wholesale telecommunications product and services competition and by reducing the administrative cost and red tape for wholesale providers to install infrastructure. In other words, its legislated position of market power could be reconsidered.

The effect of wholesale infrastructure installation "cherry picking" by NBN Co's competitors is difficult to measure or prevent without price and access regulation. If NBN Co is sold off as a single entity or disaggregated before sale, the bounds for "cherry picking" will be difficult to set, as one would expect NBN Co's sale to open up wholesale infrastructure competition.

New legislation and regulations (TLACC, 2018; TRBSCB, 2018) have reduced the barriers to infrastructure sharing, restrictive trade practices related to infrastructure access and pricing, and provided a mechanism to ensure that the telecommunications industry contribution to the provision of fixed wireless and satellite infrastructure is broadly based.

The Australian government carries out a review of telecommunications services in regional, rural and remote parts of Australia every three years (RTR, 2018). The regional telecommunications review has attracted considerable public interest over the years and provides government with valuable information.

It is reasonable, based on the success of the regional telecommunications reviews, to have periodic urban telecommunications reviews that focus separately on the wholesale and retail markets. The rationale is that government would be better informed by periodic public reviews and better placed to ensure that future problems are tackled early.

Options for NBN Co Ownership after 2022

When the NBN is built and fully operational in 2022, the future ownership of NBN Co should be addressed. There are four broad options that could be adopted, as described below.

It is unlikely that there will be political consensus about the future of NBN Co, and even within the political parties there is likely to be a range of viewpoints due to hardened ideology that often leads to detrimental outcomes for the nation.

How can a consensus be found on what to do with NBN Co after 2022? Possibly there will not be a consensus so it is vital that there be a broad review of the options.

This section aims to introduce the potential options for NBN Co after 2022, and is not an exhaustive analysis of the factors affecting NBN Co's future, but a starting point. Interestingly, each factor can be seen to affect all of the options, so discussion of a factor is not duplicated unless necessary to differentiate the effect on a particular option.

Option A. Not sold off

If NBN Co were retained as a government business enterprise for a period of not less than 10 years, there would be several benefits to government:

1. Maintaining the disruption momentum;
2. Uniform national wholesale pricing;
3. Reducing the digital divide through a focus on regional and remote telecommunications;
4. Revenue growth over time;
5. A single entity that can upgrade FTTN, FTTC and HFC to FTTP over the next five years;

6. Implementing telecommunications infrastructure security.

Disruption needs time to work its magic and the next decade will be critical to the future of the telecommunications market. A rushed sale of NBN Co puts the beneficial outcomes expected from a period of positive disruption at risk.

A key disruptive event linked to the NBN occurred on 31 March 2015 when Netflix commenced its operation in Australia.

Selected quotes from NBN Co's Corporate Plan 2018-21 highlight how the NBN is changing broadband access and usage (NBNCO, 2017):

> "At the end of FY17, 46 RSPs [Retail Service Providers] have wholesale broadband agreements in place with nbn [NBN Co] and others are on-selling services to consumers through aggregation.
>
> "End-user demand for data has grown, and will continue to grow substantially. Connectivity is playing an ever-increasing role in everyday life with the average Australian household now accessing the internet over 14 fixed and mobile devices, and forecast to have 31 internet connected devices in the home by 2021.
>
> "nbn expects consumption to continue to grow substantially over the next 10 years, driven by an explosion of video-streaming, use of multiple connected devices simultaneously and new data-intensive applications both in Australia and globally. Average monthly data usage has increased nearly ten-fold over the past five years, and is forecast to grow by 20–30 per cent CAGR [compound annual growth rate] to 2025.
>
> "94 per cent of households participate in eCommerce, including online shopping.
>
> "More than 1 million premises previously underserved or without internet now have access to fast broadband.
>
> "400,000 Australians work from home today, doubling by 2025 ... Nearly 70 per cent of regional premises use retail services on the nbn™ network to work from home."

By maintaining NBN Co as a GBE, the uniform national wholesale pricing regime can be bedded down over the decade to 2030. Maintaining a uniform national wholesale pricing regime for the next decade should be a key goal of any decision about NBN Co's future ownership. The telecommunications industry needs a period of price certainty and this option is the best approach to achieve this goal. Uniform national wholesale pricing and an improving quality of service from NBN Co provides service providers with a level playing field upon which competition can thrive.

There will be pressure from large telecommunications companies to relax the uniform wholesale pricing regime and to provide discounts to the large telecommunications companies. Every step along this path reduces the effectiveness of the disruption caused by the NBN, reduces the smaller service provider competitiveness and ultimately reduces the opportunity to provide Australia with an open, fair and competitive telecommunications market.

The advent of the NBN has provided an opportunity to reduce the digital divide through a focus on regional and remote telecommunications. As a national wholesale provider, NBN Co would have the expertise and growing experience to tackle the challenge of providing new solutions to regional and remote telecommunications.

There is a need for an ongoing program to increase the spread of fibre into regional areas and to put a new satellite into service every six years to meet increased demand in remote areas and to replace the existing satellites, which have a 15-year lifetime.

Australians living in regional and remote areas have long suffered because commercial telecommunications providers have not been able to service the demand for reliable and low-cost telecommunications products and services. NBN Co has facilitated effective competition in regional and remote areas for the first time. It would be unwise to unwind this competitive environment before it has a chance to become the norm.

The telecommunications levy for regional and remote areas should be periodically reviewed and consider customer satisfaction, demand, growth, retail competition, availability of funds for infrastructure upgrades and OPEX (operational expenditure).

The revenue that would be generated by 8.1 million premises paying $52 per month for a broadband connection (NBNCO, 2017) plus business connections will, over time, become a sizeable amount, particularly as debt is paid and the company becomes more profitable. After OPEX and future CAPEX (capital expenditure) are taken into account, the return on investment should make ownership of NBN Co advantageous to government as the years go by. Government could then look to sell off NBN Co at a time of its choosing, rather than as a rushed move to get NBN Co off its books in 2022-24.

By 2022, Australia will have a broadband network that consists of a mix of technologies including copper-based technologies and the future-proof FTTP. The cost to upgrade about 6 million premises from FTTN/B, FTTC and HFC to FTTP is about $10-12 billion. By retaining ownership of NBN Co, government could manage the upgrade pathway to the future-proof FTTP (Gregory, 2015b; Gregory, 2016b; Gregory, 2017b; Gregory, 2017d).

The next decade will be a period of national security uncertainty. Increasingly, digital infrastructure and systems are becoming a target for state actors, criminals and terrorists. As a GBE, NBN Co is optimally placed to act on government national security policy and regulations (Gregory, 2018c; Gregory, 2017c; Gregory, 2013).

Option B. Sold off as a single entity

If NBN Co is sold off as a single entity, this option immediately satisfies the "small government" ideology where GBEs are, supposedly, not needed and a government enterprise is assumed not to be able to compete with private enterprise when it comes to providing low-cost products and services with a reasonable return on investment (Melleuish, 2000; Van Onselen, 2015; Young Liberals NSW Division, 2018).

For the NBN to be sold off as a single entity consideration should be given to:

1. Viability;
2. Wholesale competition;
3. Foreign ownership restrictions;
4. Price control.

Viability

The NBN Co corporate plan indicates that, for NBN Co to be viable, it would need an Average Revenue Per User (ARPU) of $52 per month. On 10 May 2018, NBN Co reported that ARPU had risen to $44 per month (NBNCO, 2018b) and was expected to grow to $52 per month in FY21 (NBNCO, 2017).

However, there is doubt that the ARPU will reach $52 per month in FY21, especially given the limitations in predictable performance inherent with FTTN technology. ARPU has risen from $40 per month in 2010 to $44 in Q3 2018, yet NBN Co expects this figure to suddenly rise to $52 per month in a little over two years. To do so would require an increment of significant additional value that NBN Co cannot provide and is not planning to provide. NBN Co's projections (NBNCO, 2017) indicate that, by the end of FY20, it will have 8.1 million premises connected to the NBN and, by the end of FY21, 8.6 million premises will be connected out of a total 11.7 million premises. This means that NBN Co anticipates about 73-75 per cent of premises will connect to the NBN.

The Australian Bureau of Statistics (ABS) (ABS, 2018) reports that there were 14.2 million broadband Internet subscribers in Australia at the end of December 2017. Of these, there were 6,286,000 mobile wireless subscribers (datacard, dongle, USB modem or tablet SIM card and other wireless broadband, excluding mobile handsets). This means that there were 7,914,000 premises connected using DSL, Cable, Fibre, Satellite, or Fixed Wireless.

Mobile cellular providers know that, to take market share away from the NBN, providing access to more data is vital, and we are seeing evidence of this recently with the advent of "unlimited" data plans. TPG Networks recently announced that it intends to offer "unlimited" mobile data for customers on its "Brand New Australian Mobile Network" (TPG, 2018). The "unlimited" plan means that customers would get the "first 1 GB of data every day supplied at 4G LTE speeds, after which speed will be capped at 1 Mbps for the remainder of the day". The plan would be free for the first six months and customers would pay $9.99 per month after this.

NBN Co does not adequately address the threat of mobile cellular 4G/5G in its projections and it is possible that NBN Co could have a 10-15 per cent reduction in connections due to mobile cellular. There are a number of reasons why mobile phones make sense for some people: they are likely to have mobile phones; they rent; they are not prepared to endure the poor, slow and unreliable performance provided by FTTN; and, by utilising only 5G, they reduce the administrative overhead of having multiple Internet connections (Gregory, 2018b). By FY21, 5G is likely to be cost comparative with NBN Co's 50/10 Mbps product, to provide higher connection speeds than what is available via the NBN and should also provide "unlimited" data access.

It is anticipated that, by the end of 2018, the ACCC will have defined what "unlimited" means in response to a recent Federal Court decision that Telstra's use of the word "unlimited" in some advertising was misleading consumers. Telstra's "unlimited" data plans limit the connection speed to 1.5 Mbps after the 40 GB quota is exceeded on its $69 per month mobile plan (Adhikari, 2018).

NBN Co has an opportunity to increase its viability by offering products and services to government, business and industry. Over time, it is anticipated that, if NBN Co builds momentum as a wholesale provider linking government, business and industry with retail service providers, this will improve NBN Co's overall viability. NBN Co has commenced offering products and services to business, government and industry, but this direction is likely to remain a secondary focus until the NBN is built and fully operational (Viasat, 2017).

Wholesale Competition

Government legislation has introduced limited wholesale competition; however, there remains an opportunity to look at the impediments to open, fair and competitive wholesale competition, including administrative costs and red tape.

Wholesale competition is likely to motivate the privatised NBN Co to complete the all fibre access network to 93 per cent of premises. Consumers should benefit from wholesale competition (Whigham, 2018).

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Another motivation for wholesale competition would be to reduce legislative intervention, the need for the ACCC to declare services and implement price controls.

Effective wholesale competition may not occur in regional and remote Australia due to customer density and the cost of infrastructure. Before NBN Co's SkyMuster satellites were launched, the cost of broadband in remote areas was prohibitive, available capacity was limited and efforts to enter the private satellite provider market were difficult (Baker, 2017).

A privatised NBN Co would rely on the industry wide wholesale levy for the provision of wholesale broadband services to regional and remote areas. This levy is flawed because it does not have a broad base – exclusions include small business, mobile broadband services, fixed-wireless broadband services, satellite broadband services, exchange-based xDSL broadband services and inactive super-fast carriage services (Gregory, 2017e).

The question of whether other wholesale providers should be able to access the regional and remote broadband industry levy is problematic, because it would be assumed that NBN Co is already receiving the proceeds of the levy to cover regional and remote areas and the telecommunications industry is not likely to support two companies receiving funds to support the provision of broadband in the same regional and remote areas. However, NBN Co should not gain the proceeds of the industry levy if the competing wholesale provider offers service providers an improved wholesale product at the same or lower price than what NBN Co is offering.

An example of this scenario is the recent decision by NBN Co to withdraw the Fixed Wireless 100 Mbps product (Gothe-Snape, 2018). This decision, whilst in keeping with the Government's statement of expectations (DCA, 2014) for the NBN, does not adequately address the technical issues related to lower average speed connections.

The New Zealand wholesale broadband provider, Chorus, published a blog post titled "The case for 100 Mbps (or more…)" in 2016 that highlights some of the issues (Chorus, 2016) related to why the Government's statement of expectations was inadequate.

After 2022, if the privatised NBN Co is not offering a 100 Mbps Fixed Wireless product, then a competing wholesale provider that is offering a 100 Mbps product (technology agnostic) should be able to replace NBN Co as the recipient of the industry levy for areas where the competing wholesale provider is offering an improved wholesale product at the same or lower price than what NBN Co is offering.

Foreign Ownership Restrictions

Government will need to consider foreign ownership restrictions for a privatised NBN Co. If NBN Co is sold off as a single entity, then it is more likely to attract a foreign buyer or a consortium dominated by foreign partners. Would this, however, be in the nation's best interest?

Legislation for foreign ownership restrictions of a privatised NBN Co should occur. Telecommunications is an essential service and NBN Co would largely remain a dominant company owning most of the nation's vital telecommunications infrastructure under this option.

Foreign ownership restrictions are likely to significantly reduce the potential pool of purchasers with the capital necessary to purchase NBN Co and this is likely to have a negative effect on the sale price (McCarthy, 2018; Gregory, 2014b; Lattey, 2017).

Price control

The privatisation of other utilities (e.g. electricity and gas) in Australia has demonstrated that lower prices for consumers is not always an outcome. It may be necessary for the ACCC to be given power to declare wholesale infrastructure, in areas where there are less than three wholesale infrastructure providers, for the purpose of price control.

Discussion

The 2013 NBN Strategic Review included a FY25 valuation of the NBN using an EBITDA multiple of 6.0 resulting in a valuation of $27 billion (NBNCO, 2013). It achieved this figure by using the Government's Panel of Experts review EBITDA projection of $4.5 billion in FY25 (Turnbull, 2013; DCA, 2013; DCA, 2018b). The Government's Panel of Experts utilised inputs and assumptions that have been questioned. Also, the underlying models used have not been released for scrutiny (Gregory, 2014c).

NBN Co's Corporate Plan 2018-21 states that annual revenue is forecast to increase to $5.4 billion and EBITDA to $2.2 billion in FY21, providing a valuation of $13.2 billion (NBNCO, 2017). In FY21, free cash flow is projected to be $100 million.

Of interest here is the question of how NBN Co will raise the EBITDA from the projected $2.2 billion in FY21 to the Government's Panel of Experts review EBITDA projection of $4.5 billion in FY25. One approach would be to minimise CAPEX and OPEX between FY21 and FY25. Reducing the CAPEX spend could be achieved by freezing the NBN as it is when it is built and fully operational – this would mean no new satellites and no technology upgrades unless the customer pays. However, this approach is not guaranteed to bridge the $2.3 billion EBITDA gap, especially if debt is to be reduced and customer demands for better broadband are to be met.

In FY21, NBN Co peak funding is expected to be $48.7 billion broken into two components: equity funding of $29.5 billion; and debt funding of $19.2 billion (NBNCO, 2017).

A 2015 Fairfax media report quoted unidentified industry sources that said “the final sale figure is likely to be as low as $20 billion” (Clark, 2015).

By FY21 NBN Co will be the third largest Australian telecommunications company, with only Telstra (2018 EBITDA projected $10.2 billion) and Optus (FY18 EBITDA $5.089 billion) being larger.

The sale of NBN Co as a single entity will be difficult due to the financial commitment required to purchase NBN Co. A government write-off of as much as $30 billion may be necessary for NBN Co to be sold off, either as a single entity or disaggregated entities. In 2017, the Turnbull Government rejected calls for the Government’s NBN investment to be written off; however, this has not stopped debate on this matter (Smith, 2017a; Duke, 2018).

The alternative is for the Government to delay the sale or to put NBN Co up for sale hoping for market interest.

On 19 April 2018, a NAB Trade analysis (Rickard, 2018) stated:

> “Telstra’s challenges are essentially two-fold. Firstly, there’s the impact of the NBN, which is estimated to leave an earnings hole of $3.0bn pa when fully implemented. If Telstra took no action, EBITDA would fall from around $10.5bn to $7.5bn.
>
> “Telstra has a high level plan to address this, which includes productivity, capex and revenue goals. It says that it has so far delivered around $870m of benefits, mainly from productivity and cost initiatives. However, details on how it aims to address the balance are sketchy. In particular, it has yet to articulate the ‘new’ revenue sources.”

As discussed earlier, if Telstra was to split into two companies, the wholesale company could absorb NBN Co and, with an appropriate government debt repayment plan, the new wholesale company could be positioned to gain broader industry support. [While this article was going to press, Telstra made an announcement that it would split some network and wholesale assets into an organization separate from its retail activities. See the Endnote.[i]]

This should occur for three reasons: (1) Telstra shareholders would gain a share in each entity for one share currently held in Telstra; (2) the resulting size of the retail company would make it comparable to Optus, further enhancing competitive activity in the retail telecommunications market; and (3) the Government could shift existing foreign ownership restrictions from Telstra to the new wholesale company.

Option C. Disaggregated technology footprints sold off separately

The sale of the disaggregated NBN technology footprints has been recommended by the Government's Panel of Experts and the Australian Competition and Consumer Commission Chairman, Rod Sims (DCA, 2013; Duckett, 2016; ACCC, 2014a).

In a preliminary response to the Government's Panel of Experts report, the then Minister for Communications, Malcolm Turnbull, stated: "while disaggregation of NBN Co's business units (as the panel recommends) after the network is complete cannot be ruled out, now is not the time. Breaking up NBN Co would distract its management and delay the provision of high-speed broadband to all Australians" (Turnbull, 2014b).

In the Communications sector market study final report, the ACCC (ACCC, 2018b) stated that "this form of infrastructure-based competition would encourage ongoing investment in network upgrades and deliver price benefits and improved services to consumers over time".

The rationale behind the ACCC's plan for the future of the NBN appears to be based on the Government's Panel of Experts review reports.

The ACCC has recommended that:

> "The Government should continue planning for the future disaggregation of the NBN and ensure that measures are in place to enable the NBN to be split into competing networks, to provide a market structure that will facilitate greater infrastructure-based competition. The form of any disaggregation and privatisation should also be part of the terms of reference for the Productivity Commission's future inquiry into regulatory, budgetary, consumer and competition matters relating to the NBN."

This recommendation is based on the ACCC's submission to the Government's Panel of Experts review:

> "…while natural monopoly characteristics [in telecommunications] may be present in many circumstances, there may be other instances in which it will be economically efficient for there to be multiple operators of particular network infrastructure. In particular, areas with lower cost of deployment and relatively dense customer distributions may be more efficiently served by competing infrastructure" (ACCC, 2014b).

And:

> "We understand that NBN Co has introduced separate accounts for the different lines of its business, which it provides to the Government. In addition, we understand a

report was commissioned by NBN Co on OSS and BSS separation and provided to the Government, but neither the report itself nor its findings have been released publicly.

> "We consider that privatisation of the NBN following completion of the network rollout should not be undertaken in a way that limits competition in order to maximise the sale proceeds. Rather, privatisation of the NBN will provide a unique opportunity to put in place a market structure with the potential to deliver effective infrastructure-based competition, such as through the horizontal disaggregation of NBN Co by different network technologies or areas of coverage. To achieve the competition objectives, the disaggregated parts would need to be able to contest each other's customer base. In our view, this form of infrastructure-based competition would encourage ongoing investment in network upgrades and deliver price benefits and improved services to consumers over time.
>
> "We note that the Government does have a policy objective of disaggregation of the NBN once the rollout is complete. In our view, it is imperative that actions be taken to provide further detail and planning for this. We are concerned that if measures to help facilitate separation are not put in place at an early stage, such as separate OSS and BSS, it will become more costly to implement later on, which could be used as a basis for not proceeding with the separation of NBN Co. We acknowledge that it is current Government policy for the form of disaggregation to be part of the Productivity Commission's remit in examining the NBN prior to privatisation. We are keen to see that this remains the case, but also consider that anticipatory actions should continue to be taken prior to this inquiry commencing" (ACCC, 2014b).

The ACCC does not fully expand on why it is "keen to see that this remains the case", beyond the comments quoted above. A full reasoning for the ACCC's position should become evident when the ACCC makes a submission to a future Productivity Commission inquiry.

The argument put for disaggregation has several fundamental problems that are difficult to overcome.

If the NBN is disaggregated and sold off as four, five or six entities (FTTN/B/C, HFC, FTTP, Fixed Wireless, Satellite, Transit and Business wholesale), the result could be simply that one or more telecommunications companies would purchase the entities and seek to optimise a financial return from the new asset without consideration to upgrading or increasing the infrastructure footprint.

The telecommunications company that purchased the FTTP areas would be in a prime position to optimise revenue and to begin rolling out FTTP into high-value areas currently covered by FTTN/B/C. This cherry picking would have a detrimental impact on the value of the

FTTN/B/C assets and this would be anticipated during the sale process. If the telecommunications companies that purchased the FTTN/C/B technologies tried to counter this situation by rolling out FTTP outside the FTTN/C/B footprint to maintain market share, then a consumer backlash should be anticipated. It is for this reason that the FTTP footprint is likely to sell at a premium, even though many of the FTTP areas are outside major urban centres.

A disaggregated sale of NBN Co assets would require careful planning to ensure that infrastructure-based competition was able to evolve.

If Telstra purchases one or more of the technology footprint areas, then it would benefit by not having to pay itself to lease facilities and infrastructure; however, other telecommunications companies that purchase fixed-line assets should be required to pay Telstra $15 per connection per month, as NBN Co is now paying. We would then have a partial return to the market scenario between 2000-2009.

Removal of the principle of uniform national wholesale pricing will immediately unbalance retail price competition and there is a discrepancy associated with the different infrastructure lifetimes and the higher OPEX cost for copper-based technologies.

Fixed Wireless and Satellite fall into a different category and the industry levy would be needed to make the operation of Fixed Wireless and Satellite viable.

The worst-case scenario, as a result of this option, would be for none of the telecommunication companies that purchased NBN Co assets to upgrade or to expand their infrastructure footprints. Whilst this is not anticipated, the result could be a very slow upgrade pathway to competitive, all-fibre networks and a short-term adoption of 5G as an alternative infrastructure that offers headline connection speeds that can be marketed as being "better than FTTN/B/C".

Option D. Disaggregated technology footprints (excluding satellite and fixed wireless) sold off separately

Option D follows from Option C with the exception that NBN Co's Fixed Wireless and Satellite assets would be retained and continue to be funded partially through an industry levy.

NBN Co's two satellites have an approximate 15-year lifetime before they need to be replaced and it takes 4-6 years from contract signing to when a satellite can become operational.

An increase in the number of Fixed Wireless and Satellite residential and business connections and an increase in demand for improved connection speeds and capacity mean that the industry levy to support the provision of regional and remote broadband products and services may need to be adjusted.

Direct government control and management of every aspect of providing telecommunications services to regional and remote areas will help to bridge the digital divide and to ensure that new products and services are provided to regional and remote areas. It is a government responsibility to ensure that people living in regional and remote areas have access to eGovernment digital services, education and health. The next decade will see significant change in how eGovernment digital services are provided and what is on offer. With digital transformation a national priority, it is vital that government continue to focus on building telecommunications capability and capacity in regional and remote areas.

The provision of telecommunications to regional and remote areas is vital for this nation's future role in the global digital economy and to ensure that everyone, irrespective of where they live or work, is able to access digital services at reasonable cost.

There is no reason for people living in regional and remote areas to be part of an ideological lottery associated with the sale of NBN Co.

Government retention of the Fixed Wireless and Satellite assets does not prevent the assets being sold in the future. Retention would provide the government with the time necessary to ensure that the competitive and pricing outcomes from the sale of the rest of NBN Co have been successful and, if not, that remedial action has been taken before privatisation of Fixed Wireless and Satellite occurs.

Conclusions

By 2022, when the NBN is expected to be built and fully operational, the NBN will provide Australia with vital telecommunications infrastructure and for the first time every Australian should reasonably expect to be able to get access to broadband, irrespective of where they live and work, at reasonable cost.

The NBN has been a disruptive influence on the telecommunications market, particularly impacting Telstra's market share and revenues.

Disruption should not be confused with chaos and the period after the sale of NBN Co as a disaggregated entity could be chaotic if legislation and regulations do not adequately provide for access, pricing and competition. There is nothing to be gained by the government setting out on a chaotic path due to ideology and it is for this reason that the telecommunications industry should consider carefully what happens next.

Disaggregation of NBN Co could reduce or remove the positive disruption that the NBN is having on the telecommunications industry. Telecommunications companies are looking beyond handsets and bitstream in an effort to become technology companies and to build additional revenue streams. A rush to sell off NBN Co could remove or significantly reduce the positive disruptive effects that the NBN is having on the industry, and the telecommunications industry could revert to circa 2005.

Options A, B, D and C, in that order, are preferred based on the discussion and analysis presented.

Option A provides the nation with the greatest opportunity to benefit from the disruptive nature of the NBN whilst focusing on providing a ubiquitous future-proof fibre access network and reducing the digital divide in regional and remote regions.

The breadth of topics, perspectives and factors that must be taken into account before a decision is made as to what should be done with NBN Co, after the NBN is built and fully operational, is considerable.

For this reason, the government should commission public inquiries by the ACCC, the Australian Communications Consumer Action Network, the Australian Communications and Media Authority (infrastructure technologies, standards and security) and Infrastructure Australia prior to the legislated public inquiry by the Productivity Commission into the sale of NBN Co.

Telecommunications is an essential service and, in the next phase of the deregulation process (possibly the last phase?), the government should put in place legislation and regulations that ensure that the nation gains an open, fair and competitive telecommunications market whilst providing outcomes that are in the long-term interests of the nation and end users.

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Endnote

On 20 June 2018, Telstra announced, as part of its Telstra 2022 plan, that it was "establishing Telstra InfraCo, a new standalone business unit within Telstra" that would be "accountable for our copper and HFC networks; all our fibre network that is not dedicated to supporting mobiles; all ducts, pits and pipes; property including exchange buildings and data centres; and international and domestic subsea cables. These assets will be combined with Telstra Wholesale and the teams in Telstra Operations that provide services to nbn co" (Irving, 2018). This announcement provides Telstra with the opportunity to participate in the future sale of the NBN. Telstra could spin off the business as a separate ASX-listed company, take on infrastructure investors for a future purchase of the NBN, or part of the NBN, and effectively follow what happened in New Zealand with Telecom New Zealand becoming Spark and Chorus. The potential impact of the Telstra announcement on Australian wholesale telecommunications reform is left for future research.

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Data Transfer via UAV Swarm Behaviours

Rule Generation, Evolution and Learning

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Abstract: This paper presents an adaptive robotic swarm of Unmanned Aerial Vehicles (UAVs) enabling communications between separated non-swarm devices. The swarm nodes utilise machine learning and hyper-heuristic rule evolution to enable each swarm member to act appropriately for the given environment. The contribution of the machine learning is verified with an exploration of swarms with and without this module. The exploration finds that in challenging environments the learning greatly improves the swarm's ability to complete the task.

The swarm evolution process of this study is found to successfully create different data transfer methods depending on the separation of non-swarm devices and the communication range of the swarm members. This paper also explores the resilience of the swarm to agent loss, and the scalability of the swarm in a range of environment sizes. In regard to resilience, the swarm is capable of recovering from agent loss and is found to have improved evolution. In regard to scalability, the swarm is observed to have no upper limit to the number of agents deployed in an environment. However, the size of the environment is seen to be a limit for optimal swarm performance.

Keywords: Robotic Swarms, Machine Learning, Hyper Heuristics, Mobile ad hoc networks

Introduction

Augmenting Mobile ad hoc network (MANET) topologies with unmanned autonomous vehicles has recently been investigated in the literature (Llorca, Milner & Davis, 2007; Fraser

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& Hunjet, 2016; Zhang & Quilling, 2011; Dixon & Frew, 2007; Henkel & Brown, 2008; Zhao, Ammar & Zegura, 2004; Zhao & Ammar, 2003). The techniques found include: distributed optimisation (to increase network survivability); relay chaining Unmanned Aerial Vehicles (UAVs); and data ferrying when connectivity cannot be maintained. Each of these techniques addresses the networking problem well in its specific context, but does not operate well in alternative environments; e.g. a distributed optimisation method for increasing survivability is not applicable to a disconnected network where data ferrying is necessary. Such techniques can be considered expert-system-type approaches and suffer from the *no free lunch* dilemma (Wolpert & Macready, 1997), in which any one method will solve some problems well but perform poorly in others. This issue is not confined to the communications domain, existing in many disciplines. Hyper-heuristic (HH) approaches, which allow for generation and real-time selection of heuristics to address a given problem space, have recently been proposed as a method to address this issue (Poli & Graff, 2009).

In this paper, we examine mobile networking devices for sparse communication. Within this domain UAVs can aid in data communication between two nodes via *relay* or *ferry* methods, with the former having lower packet delays, and the latter spanning greater distances. Prior works (Henkel & Brown, 2008) have addressed communications using one *or* the other. However, for an agent to make this decision autonomously, apt network information and prior human control must define the network circumstances for each method to be used. This is time consuming and requires extensive testing. Finally, if a collection of agents select from a discrete set of transfer methods, the group will require unification of action selection via a plan consensus, such as auctioning (Pourpanah, Tan, Lim & Mohamad-Saleh, 2017) or voting (Valentini, Ferrante, Hamann & Dorigo, 2015). This will, in turn, require a high level of shared environment knowledge, as agents must make an educated assessment. This combination of environment knowledge and action planning comes at a large inter-group communication cost, which is undesirable in restricted communication environments and is not scalable.

To counter the above issues Swarm Robotics is a growing research topic. Swarms have a basic control system which, when implemented in large groups, exhibits *emergent behaviour*. That is, these units can individually perform basic tasks, which collectively produce complex global results. These swarms are praised for being decentralised, robust, scalable and flexible (Brambilla, Ferrante, Birattari & Dorigo, 2013). However, standard swarm design requires detailed testing and evaluation to develop these emergent behaviours. By having the swarm learn and evolve individually it is believed the robustness and flexibility will increase, while maintaining scalability and reducing the need for manual adjustment. The main contribution of this paper is the development of a simulated learning and evolving swarm, which must transfer a number of data packets between source and sink network 'base stations' out of communication range with one another. A swarm of the proposed robotic agents evolves rule-sets and learns appropriate rules for transferring the time-insensitive packets via requesting transmission from the bases, transmitting amongst themselves, and moving about the environment. The novelty of this intelligent swarm is the combination of standard swarm properties with online (during operation) reinforcement learning, and offline (post-operation) heuristic evolution. To fully explore the value of this combination, evolution experiments without the learning process are also conducted.

The remainder of this paper is structured as follows: a background of UAV data transfer methods, collaborative agents, rule learning and HH is given in *Related work*; the swarm agent design, including agent knowledge, action processing, and learning/evolving, is presented in *System design*; further specifications of the communication bridging problem and reward function are presented in *Application scenario*; details and results of the experiments explored in this study are presented in *Experiment Setup* and *Experimental Results*; and finally the paper is concluded in *Conclusion and Future Work*.

Related Work

The two most popular methods in the literature of having a MANET of UAVs transfer data between geographically dispersed network nodes are relaying and ferrying.

Relaying (Llorca et al., 2007; Zhang & Quilling, 2011; Dixon & Frew, 2007; Henkel & Brown, 2008; Lee, Fekete & McLurkin, 2016; Mehrjoo, Sarrafzadeh, & Mehrjoo, 2015) sees the agent place itself between the two nodes, thus halving the transmission distance each packet must be sent per hop. A collection of units may evenly disperse about this distance, creating a multi-hop chain (Llorca et al., 2007; Dixon & Frew, 2007). However, the relay method is range-limited, based on the number of relays used. Each relay in the chain must have a receiver and sender neighbour: thus, the maximum range of the relay system is $R \cdot (k+1)$, where R is the stable communication range of the relays, and k is the number of relays.

The ferry method (Fraser & Hunjet, 2016; Henkel & Brown, 2008; Zhao et al., 2004) has each agent move to be in range of the transmitting device, where it collects a number of packets equal to its buffer size. The agent then physically moves toward the receiver and, upon communication-link establishment, will transfer the buffer content. In *conveyor belt ferry* (Henkel & Brown, 2008) each agent makes this full travel, while in *Newton's cradle* (Fraser & Hunjet, 2016) each unit ferries from the closest sending neighbour to the closest receiving neighbour. This sub-method of ferrying can be seen as a hybridisation of ferry and relay, though is only one possible splicing. In general, the ferry method has much greater delay time and energy consumption, but can span much greater distances (Zhao et al., 2004).

In Henkel & Brown (2008), an adaptive agent is proposed that switches between relaying and ferrying approaches based on distance. However, the work only suggests a binary swap between the two extremes (relaying and ferrying) rather than utilising features of both. Additionally, the decision of when to switch methods must be calibrated manually in this approach.

A fleet of adaptive Unmanned Aerial Systems can be thought of as a collection of intelligent agents. The literature covers multiple philosophies for the implementation of agent coordination. We briefly describe two of these, *swarming* and *teaming*, below. Swarm agents are often very simple, as seen in Lee et al. (2016), Mendonca, Chrun, Neves & Arruda (2017) and Kanakia, Touri & Correll (2016). These agents lack object permanence via environmental modelling, often use a human-devised hard-coded action rule list, or have limited direct messaging between members. Furthermore, the actions performed by the agents are often not selected to explicitly solve a goal. Rather actions are triggered via stimuli. These stimuli-action relations are often set by humans to orchestrate a greater swarm behaviour (*emergent behaviour*), which leads the swarm to achieve an objective of which the agents have no understanding. Consider as an example *swarm taxies* (Timmis, Ismail, Bjerknes & Winfield, 2016), in which units fluctuate between travelling toward and away from the swarm centre. When a light source varies the ratios of these two actions, the swarm can drift toward an illuminated goal location without the agents directly attempting to do so.

A team of intelligent agents (Johnson, Choi, & How, 2016; Riccio, Borzi, Gemignani, & Nardi, 2016) will have a collection of independently capable agents interact. These agents often have shared operational plans and detailed environment model sharing. Some promote consensus or distributed optimisation-based methodologies (Johnson et al., 2016). Such approaches require time to reach a decision, high network bandwidth, and complex onboard computations. These methods may also be vulnerable to malicious data injection, which would confuse or stall the group (Rada-Vilela, Johnston & Zhang, 2014). Additionally, some approaches require rendezvous (Lee et al., 2016) of the agents, which creates a failure chain-reaction, as one member failing will cause rendezvous members to stall in a waiting state.

In this paper we propose the first design of a robotic agent with the strengths of both approaches, namely: the complex problem solving of team robotics; and the robustness, scalability, flexibility and decentralisation (Şahin, 2004) of swarm robotics. By using swarms with emergent behaviours, online planning is not required and the swarm is not affected by the above issues.

Machine learning (ML) is a common approach applied to complex problem-solving in the literature. Action rules are used in Markovian Decision ML, such as Monte Carlo Tree Search

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(Ayob & Kendall, 2003; Kao, Wu, Yen & Shan, 2013; Gelly et al., 2012) and Temporal Learning (Szepesvári, 2010). In these studies, a rule links a single state to an action, with a state fully defining all variables of the agent and observed environment at the time-step. In this paper we propose agents hold a collection of rules, with each linking a state condition and an action to perform. That is, rule $p = \{c,a\}$, where c defines only some of the variables of a full agent state, and a is a specific action from all actions, **A**. The rule is scored via the reward of the action.

One approach for creating these rules is heuristic generation (Løkketangen & Olsson, 2010; Keller & Poli, 2007; Bader-El-Den, Poli & Fatima, 2009; Burke, Hyde, & Kendall, 2012). In this approach the known heuristic methods, here ferrying and relaying, are broken into components. The system creates its own heuristic by randomly re-assembling these components into a set of rules. This has been noted in the literature to be much more computationally expensive than selecting from complete heuristics, though the produced heuristics can be specialised toward a problem domain (Burke et al., 2013). Additionally, the granularity of heuristic decomposition is an important consideration: large granularity will restrict the system's flexibility, while small granularity can overly expand the search space (Bader-El-Den et al., 2009).

We argue that the combination of heuristic generation and ML provides a stable yet flexible robotic swarm, which may more expressly adapt its behaviour to solve data transfer problems.

System Design

This section presents the design of the robotic swarm unit. Each unit holds basic information about other swarm members and other devices utilised for the problem. In each time step, the swarm communicates with its peer neighbours (other swarm nodes in range) or moves about the environment.

Agent Knowledge

Unlike a collection of intelligent agents, the swarm agents of this study have limited sensing ability and shared information. Each agent is aware of its 'neighbourhood', *i.e.* all agents that are within communication range, R, at the current time step. Each neighbour advertises its relative location, including distance and angle, and if it currently holds a data packet. An agent also keeps a record of all *known* agents. This record consists of the known agent's ID, its last known location, and the age of the sighting, which is incremented each time step. With this knowledge, an agent is able to plan movements in relation to others outside its communication range. This memory prevents an agent becoming stranded, should it stray out of communications range, as seen in (Timmis et al., 2016). At each time step all neighbours are added or updated to this *known agent* list, where newly found agents are added, and prior known agents are updated with current locations.

Also within the time step, agents request *known agent* data from neighbours. At the receipt of this data, an agent updates its records to reflect the most up-to-date information (consolidating the records from neighbours and itself, using the record with lowest *age*). This process allows a co-swarm member's location to be promulgated through the swarm in a 'multi-hop', peer-to-peer fashion. This allows the swarm to make more informed decisions: note that, in the absence of this information, localised decisions are still made.

Additionally, if a *known agent* record states an agent should be in communications range, but the agent is not found during the neighbourhood update, it is assumed that it has moved since the *known location* record was made. The entry is thus removed, as it is confirmed to be no longer correct. Finally, each agent is provided with the sink device's location, which prevents an environment searching process to be conducted at the beginning of an experiment.

Action Targeting

Using the above knowledge, an agent will perform actions in relation to fellow swarm members (SMs) and/or non-swarm devices (bases). To select the target(s) of action focus, the following filters and selectors are used: agent type, direction and position. These restrictions allow the action to be more specific in its application, and thus more complicated behaviours to be performed by the swarm. The agent type filter restricts the interactions to only SMs, only bases, or *both* (no filter). The direction filter restricts to only SMs/bases toward or away from the sink location (relative to planning agent's position) or *any direction*. Finally, *position* defines the single or group of SM/bases to be used for the action. This requirement finds the member closest to the agent, second closest to the agent, furthest from the agent, SM/base closest to the sink device, all SMs/bases in communication range, or all SMs/bases in the *known agent* list.

With these targeting filters and selection method, an agent is able to define a collection, which may be of size one, to dictate the focus of the action execution.

Agent Mobility

The movement of agents is limited to attraction and repulsion of targetable agents in the environment (see *Action Targeting*). This collaborative movement planning is known as 'virtual forces' (Imaizumi, Murakami, & Uchimura, 2013; Vieira, Govindan, & Sukhatme, 2013). Using a target collection, force vectors are calculated and summed to form a single movement plan as follows:

$$V_a = p_{target} - p_{agent}$$
$$V_r = \frac{1}{p_{target} + p_{agent}} \tag{1}$$
$$V_{move} = \frac{\sum_{i=1} V_{a,i} + \sum_{i=1} V_{r,i}}{\left|\sum_{i=1} V_{a,i} + \sum_{i=1} V_{r,i}\right|}$$

where V_a, V_r are the attraction and repulsion force vectors, and p_{target}, p_{agent} are the locations of the respective units.

Reinforcement Learning

To learn the best actions to take in each time-step, Q-learning (Szepesvári, 2010) is utilised over the swarm operation. This learning equation is defined as

$$Q(c_t,a) = Q_t(c_t,a)(1-\alpha) + \alpha(\rho + \gamma \cdot Max(Q(c_{t+1},a))) \tag{2}$$

where $Q(c,a)$ is the quality score for rule {c,a} (condition, action), γ is the future rule discount factor, α is the learning rate, ρ is the action reward and $Max(Q(c_{t+1},a))$ is the predicted maximum quality score of the next rule. At each time step a greedy selector is used, selecting the rule with condition c being true and the greatest Q value. Additionally, an adaptation of QS-learning (Ribeiro, Pegoraro & Reali Costa, 2002) is used to accelerate learning. QS-learning is used in Ribeiro et al. (2002) to share Q value learning with similar states. In Ribeiro et al. (2002) 'similar' is defined as geographically close location states. In this work *conditions* are explored rather than fully defining states; therefore QS-learning shares rewards with other true-condition rules which hold matching actions.

Evolution

After a set number of learning cycles, or when the objective has been completed, the learning process is ended and the higher level HH Evolution (HHE) is implemented. In this stage, each agent is judged on its contribution toward the objective(s). Any agent that contributed below the mean has its rule-set mutated. This requirement prevents the HHE adjusting relatively functional agents.

To determine the quality of each rule, during the simulation a secondary score, *HHScore*, is assigned to each rule, in each agent, similar to the Q value. This HHScore uses limited back-propagation learning, inspired by TD(λ) (Szepesvári, 2010). In this study, BP_{depth} is a past-rule depth to back-propagate with no decay, while traditional TD(λ) back-propagates all rules explored thus far, with a learning decay rate of λ. It is seen that this adaptation reduces required memory storage of each agent, as only the last BP_{depth} rules must be stored. It is also seen that equivalent results will be produced when $\lambda^{BP_{depth}} \rightarrow 0$. In this study the *HHscore* value of the last BP_{depth} rules is adjusted via

$$HHscore_t = HHScore_{t-1} + |\rho|/\rho \tag{3}$$

This inclusion of HHscore allows the offline evolution to find the best over-all rules, rather than only the best at the end of the simulation. As an example of this HHScore requirement, a 'collect from base station' rule may be Q-value-positive at the start of the simulation, when the action is required; but the Q-value will become low at the end of the simulation, when there are no packets to collect. The HHscore of this rule will not so rapidly decrease, and will be reported to the HH evolution as a quality rule.

During the mutation of an agent's rule-set, the rule with lowest HHscore randomly has its *condition* or *action* regenerated.

After these changes are made all agents have rule HHscores and Q-values reset and the operation is restarted, with the agents at their original geographical position.

To summarise, the Q-learning is a short-term, online learning process, which is used for in-field action control. The HHE is the long-term improvement, which shifts the available rules towards an optimal set in the *heuristic space*. Figure 1 shows the overall cycle of these two iterative processes.

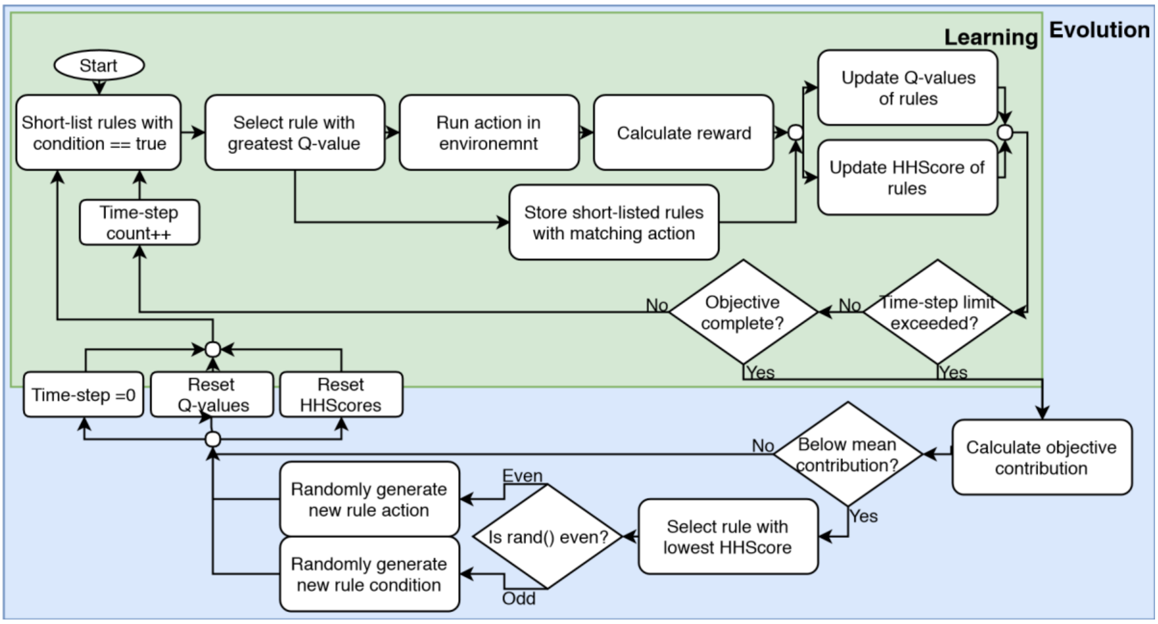

Figure 1. Flow diagram of both iterative processes

Application scenario

The Multi-Agent Simulator of Networks (MASON) (Laboratory & the GMU Center for Social Complexity, 2017) Java-based discrete event simulator is used to create an experimental simulation environment to test the proposed approach. As presented in the *Introduction* section, the swarm agents are tasked with moving data-packets from a source base to a sink base. As such, agents can only send and receive packets from neighbouring units. Furthermore, for this experiment, only one copy of a packet exists at a time, i.e. broadcasting and network flooding are not explored. This constraint was added to reduce the network load, allowing the swarm to operate in communication-restricted environments. It should be noted, however, that this restriction will result in the permanent loss of data if a swarm individual holding the data is lost. Finally, a simplistic network model is used, assuming symmetrical wireless range.

Wireless range equation

To model the communication range between all nodes, the log-distance path loss model (Rappaport, 1996) is used. The propagation path loss (in dBm) between nodes is

$$P_{loss,db}(d) = P_{loss}(d_0) + 10l \cdot \log(d/d_0) + X(\sigma)_{db} \quad (4)$$

where $P_{loss,db}(d_0)$ is the loss at a reference distance, l is the path loss exponent and $X(\sigma)_{db}$ is a Gaussian random variable, with standard deviation σ. For this study, a Wifly radio module is modelled (Networks, 2011). This unit has an effective isotropic radiated power (EIRP) of +12dBm and a signal strength receiving threshold of -83dbm. This yields a link budget of 95dB.

In this initial testing, the fading variable, $X(\sigma)$ is set to zero, allowing for agent learning and evolving to be explored in a stable environment. A high path loss exponent value of 5 is used, representing the agents operating in an urban environment with high specular reflection (Faria, 2005).

Reward calculation

In this application the action reward, ρ in (2), is found each time-step via the sum of relevant packet scores. A packet's score, f_p, at each time-step is defined as

$$f_p = dist_{sink,t-1} - dist_{sink,t} \quad (5)$$

where $dist_{sink,t}$ is the physical distance from the sink device at time-step t. This is inspired by geographical routing (Ghafoor, Lloret, Sadiq & Mohammed, 2014).

This equation scores the packet via the improvement in distance from the sink device within the time-step.

Each action reward is the sum of an action-cost and rewards from three collections of packets: those held by the agent throughout the time-step (ph); those newly received by the agent in

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the time step (pr); and those sent by the agent in the time step (ps). Additionally, to prevent over scoring, a symmetric logarithmic function is performed on the packet rewards. The action's fitness, or reward, thus becomes:

$$\rho = \sum_{i=1}^{ps} \log(|f_{p,i} + 1|) \left(\frac{|f_{p,i}|}{f_{p,i}}\right) + \sum_{i=1}^{ph} \log(|f_{p,i} + 1|) \left(\frac{|f_{p,i}|}{f_{p,i}}\right) + \sum_{i=1}^{pr} \log(|f_{p,i} + 1|) \left(\frac{|f_{p,i}|}{f_{p,i}}\right) - Cost_a \tag{6}$$

By scoring for sent packets the agent is encouraged to transfer packets onward; by scoring held packets, the agent is encouraged to move toward the sink device; by scoring received packets the agent is encouraged to position itself where other agents may transmit to it. It may be noted that a packet transfer will lead to two rewards: one agent is rewarded for sending, the other for receiving. This scoring was implemented to encourage cooperation between swarm members. Finally, by adding an action cost a simulated energy conservation is implemented into the agent learning. In this study, movement actions will have a greater cost than transmission actions, which represents the battery consumption difference between making a fixed-altitude forward motion with a quadcopter and operating a low-range radio adaptor.

This fitness function requires the packet duplication-free restriction: should packet broadcasting be permitted, it is theorised all agents will learn and evolve rules to maximise ps based scores. This will be optimal locally but globally will congest the network.

Experiment Setup

Behaviour Evolution

In the first experiment, the ability of the swarm to evolve new behaviours to suit different environments is explored. Therefore, the base units are statically placed at different distances apart: 95, 113 and 128 distance-units. In each of these base deployments, three levels of background RF noise are explored, giving $P_{loss}(d_0)$ values of: 45 dB, 36 dB and 30 dB. Given the receiver sensitivity of -83dBm and the path loss model described by (4), this yields a maximum reception range, R, of 10, 15 and 20 units respectively.

These 9 experiments test the ability of the swarm to evolve and learn behaviours appropriate for the given task.

Mid-flight failure

In the second experiment, the ability of the learning and HHE to cope with losses is tested by the periodic removal of agents during the simulation. This removal emulates the stochastic and error-prone environments these agents may be exposed to, including hardware failure, such as batteries or motors, and unknown hostile activity. When an agent is 'removed' it is not able to receive or transmit packets, nor able to announce its presence for neighbourhood updating. However, other agents do not *automatically* remove the lost agent from their 'known agent' lists unless the lost agent's absence is observed, as discussed in subsection *Agent Knowledge*.

When an agent is lost, two methods are explored for re-populating the swarm: mid-mission and post-mission re-population. It is assumed an endless supply of agents are held for re-population. In the former method, the unit deployment system is assumed to be fully aware of the environment and activates new units, with newly generated rule-sets, one time-step after a unit is removed. The latter method, post-mission re-population, has the swarm complete the operation with the reduced swarm size; and only after the evolution process, when the agents are being re-deployed, will new members be introduced. For this latter re-population method, two sub-approaches are explored: one in which the new agents generate new rule-sets; and the other with agents being implemented with the rule-sets of the lost agents, or *cloning* the lost agent.

Results from this testing aim to explore both the swarm's resilience to minor failure and the ability of the evolutionary algorithm to adjust from a major failure.

In all the tests, R is set to 15, the distance between bases is 113, and a constant agent removal interval of 3,000 time-steps is used.

Scalability

As an exploration of the scalability of the swarm, that is, the ability to operate effectively irrespective of the number of agents implemented in the swarm, the third experiment explores a range of base separation distances the swarm must cover, with a range of swarm members. This exploration also furthers the examination of the swarm to adjust its behaviour for a given environment. The swarm sizes explored are between 2 and 30 swarm members, in increments of 2. The distance the swarm must transmit data is based on the equal shifting of both the latitude and longitude of one base agent. This gives total base distances via the hypotenuse of the isosceles right triangle with sides, s, between 10 and 490, with increments as seen fit. These swarm and environment ranges are seen to adequately demonstrate the scalability of the swarm, without introducing excessive computation requirements. In this experiment the background RF noise is set to a constant value, resulting in $R=15$ units for communication range between agents.

As a comparison for this exploration, a theoretical, static-behaving relay swarm is examined. Each static swarm member has an allocated fellow swarm member or base to transmit to, and will only move to reach communication with this device. As such, the execution time is the maximum agent movement time, along with the transmission time, which is directly proportional to the number of packets, which in this study is 20. This leads to a theoretical execution time of

$$\mathrm{T_{relay}} = \sqrt{2 \times \mathrm{s}^2} - \mathrm{R} \quad (7)$$

Learning contribution

The final exploration of this study validates the inclusion of the learning algorithm in the autonomous behaviour process. In this study, the swarm agents continue to examine rule value via the *HHScore* parameter, and undergo HHE. However, in each time-step, rather than selecting rules via the highest Q-score, agents use a random selection of the rules with true conditions. This increases the responsibility of the evolution process to create rule-sets that have specific, appropriate rules for all states observed.

For this test-set, only R = 15 is explored, for the three base distances, 95, 113 and 128.

Settings

In all the tests of this exploration, the Q-learning variables (α and γ) are set to values of 0.1 and 0.9, respectively. γ is set as seen in literature (Ribeiro et al., 2002), while α is tuned for this study. Online learning rate adjustment is not used in this work, as each problem instance is seen to have a different optimal learning rate, meaning the required exploration would be too computationally expensive. As such, the HHE incorporated this static learning into the problem in which it is adapting. The BP_{depth} value is set to 10 after exploratory testing. The action cost penalties are 0.9 for movement, and 0.1 for all other actions. The learning and evolution process is repeated as many times as possible within 1,000,000 time-steps, a value chosen to ensure reasonable simulation time.

For this study, the swarm is tasked with transferring 20 packets within the time limit, T_{fail}, which for the majority of tests is set to 20,000 time-steps. This limit is imposed to have solutions created of meaningful value and to force a minimum number of evolution steps over the trial. For the scalability experiment, T_{fail} is set to 50,000 to accommodate the larger environment navigation time.

For all results, the fitness of each evolved solution is measured via

$$f_{it} = \frac{T_{fail} - T}{T_{fail}} \quad (8)$$

where T is the time taken to transfer all packets.

Each agent holds 50 rules. Initially 12 of these are human designed, inspired from ferrying and relaying heuristics. Some example ferry rules are shown in Algorithm 1. The other 38 rules are randomly generated at agent initialisation. The random generation process uses a grammar with a granularity high enough for a large range of rules to be created, without the evolution process being stalled by an overly broad behaviour space.

Algorithm 1 Example of some human made rules for ferrying

If (holding packet) **then**
    send packet to target(no_filter, toward_sink, closest)

if (holding packet) **then**
    move(attraction, target(none_swarm, toward_sink, closest))

if !(holding packet) **then**
    move(attraction, target(none_swarm, away_sink, closest))

if (neighbours ∋ base_agent) and !(holding packet) **then**
    collect packet from closest base

In regard to the evolutionary search method, an Adaptive Iteration Limited Threshold Accepting (AILTA) (Misir, Verbeeck, De Causmaecker & Berghe, 2010) move acceptance is used for local-optimal solution exploration.

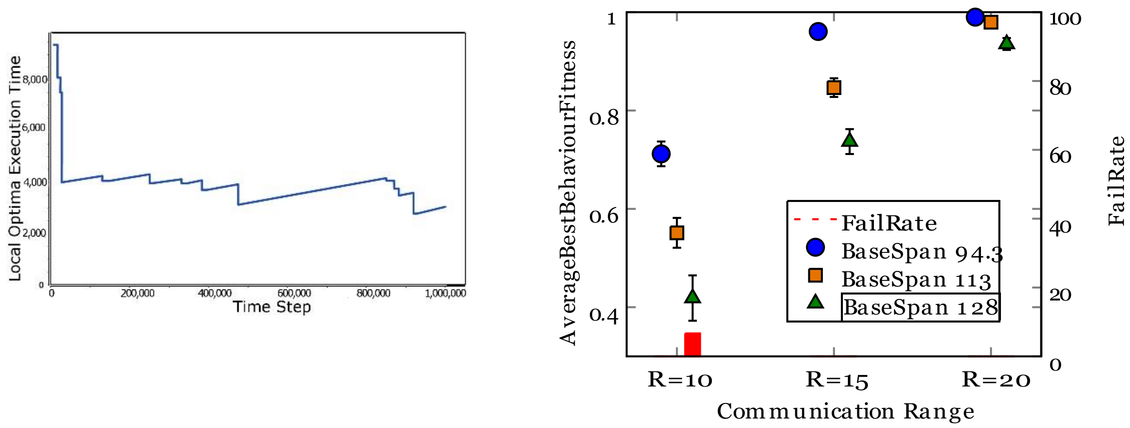
In all experiments, except scalability, a swarm of 8 units is implemented.

Furthermore, in most experiments, each simulation is run 30 times with different rule generation seeds. This prevents statistical anomalies and provides adequate data for a 90% confidence value to be determined. For scalability, only one simulation is run per swarm scale, per environment size, due to the high volume of simulations required for the experiment.

Experimental Results

Behaviour Evolution

In Figure 2a an example of the evolution process for the first test case is shown. Each change in the local optima data delivery time (vertical axis) indicates a full simulation run result. From time 0 to 400k new local optima are found approximately every 100k time steps. Then at 500k a local optimum is found that cannot be surpassed. The system continues to explore without better results, increasing the acceptable threshold to escape this local optimum with AILTA. At 820k the cusp of a new solution-space optimal area is found, which leads the evolution to the best-found rule-set at 910k. This shows that throughout the one million time-steps the system is always evolving and improving, rather than stagnating at local optima.



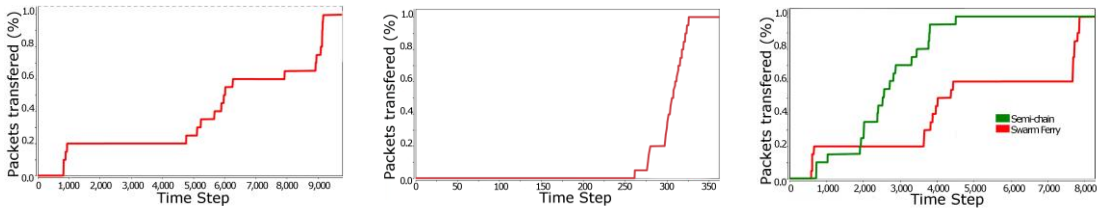
(a) Example Evolution of Data Delivery Time

(b) Mean data delivery time and 90% confidence error margin for post-evolution rule-sets

Figure 2. First test set, exploring three swarm unit communication ranges, and three base distances ('BaseSpan')

In Figure 2b the mean best fitness of all 30 evolution executions is shown for the three RF noise levels and three static base positions, along with 90% confidence intervals. In addition, the red bar shows the fail-rate (right vertical axis) where failure is defined as the system not evolving a rule-set which can transfer all packets within the time limit.

As can be seen for the more challenging scenario instances, with smaller R values and greater base separation, the system not only takes longer, on average, to complete the data transfer but the confidence intervals are increased. The former of these issues is expected, as more time-consuming methods must be used to achieve the objectives. The latter issue indicates that the harder the problem instance, the more susceptible the swarm is to the rule generator seed. This leads to larger variations in the solutions found.



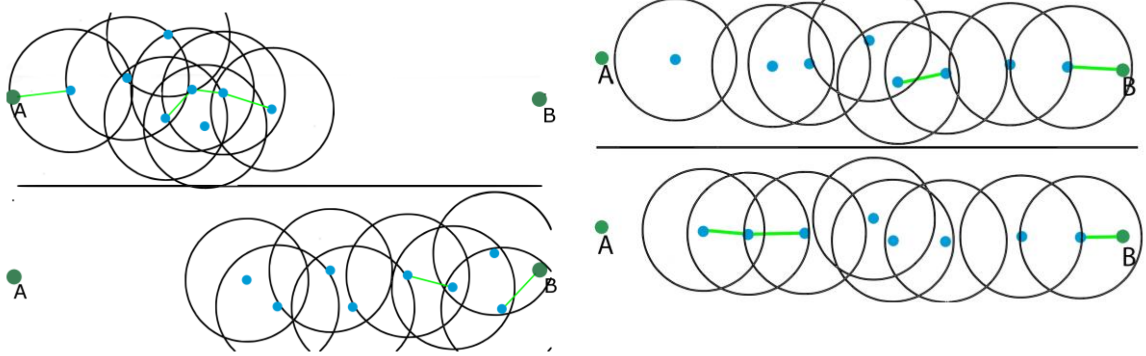
(a) *Newton's cradle* being used by swarm with R=10. Swarm is in position at 5.5k and data is transferred with some delays (6k-8k) due to member misposition.

(b) Data relay technique at R=20. Some time for swarm to position itself, then rapid data transfer.

(c) When R=15 the swarm evolves *Semi-chain* (green), with constant transfer, or *swarm ferry* (red), with bursts of transfers.

Figure 3. Packet transfer vs time step for post-evolution solutions

In Figure 3 the packet transfer process can be observed by recording the percent of packets delivered to the sink base over time-steps. These recordings are taken from the post-evolved rule-sets with noteworthy emergent behaviours. In low communication range tests with a short travel distance (when bases are 95 units apart), *Newton's cradle* transfer predominantly emerged, Figure 3a, while larger communication ranges (R=20) allow for relay chains to be established in all base separations, Figure 3b. The most variant cases are when the two bases are at maximum separation (128 units), with communication range, R, of 10 or 15. In these tests, relaying is often not achievable, while standard ferrying is too time-consuming, and is avoided due to high action costs, thus different ferry-relay hybridisations are evolved, Figure 3c. These data transfer methods have not been found in the literature and are thus labelled and discussed.



(a) Swarm ferry. The entire swarm moves from base ‘A’ to base ‘B’.

(b) Semi-Chain. The leftmost swarm member is seen to be ferrying between the end of the chain and the Base ‘A’.

Figure 4. Swarm visual representation. (Blue circles being the swarm units, black rings being the unit’s communication range, larger green circles are base devices, lines between the units/devices are packet transfers.)

In some cases, *swarm ferrying* is evolved. This has the swarm as a whole move from source to sink, while maintaining communication range with one another. When one agent (the *source relay*) is by the source, it relays data throughout the swarm until all agents have full buffers. The swarm then taxis toward the sink and, upon one agent making contact, the data is relayed through this agent. The swarm as a whole thus has a range of (R, $R\times(swarmSize+1)$); therefore units have less travel time than a full ferry process. This method is visualised in Figure 4a.

The second observed behaviour is the *semi-chain*. In this method the swarm builds relay chains starting at the sink, source or both. When the swarm size is not great enough to finish the chain, or some members of the swarm fail to fully extend the chain, the remaining distance is covered by one or two units ferrying the distance. This is shown in Figure 4b. From these diverse strategies being formed by the swarm evolution, it can be seen that the desired flexibility of this system is being achieved.

Some post-evolution, machine-generated rules, which were utilised by specific agents in the *swarm ferrying* behaviour, are listed in Algorithm 2 and 3. These rules are more specialised to a specific role within the swarm, which shows that HHE encourages heterogeneity.

Algorithm 2 Example of evolved rule for instigating swarm ferry

if (last action==move) or (has neighbour) or (holding packet) **then**
move(repulsion, target(no_filter, any_dir, all_in_comm_range))

if neighbourhood ∋ swarm_member **then**
move(repulsion, target(no_filter, toward_sink, furthest))

if (last action==send) or (neighbourhood ∋ swarm_member) **then**
wait

Algorithm 3 Example of evolved rule for source relay of swarm ferry

if !(target(no_filter, toward_sink, closest_to_sink) has packet) **then**
send packet to target(Agent, toward_sink, furthest)

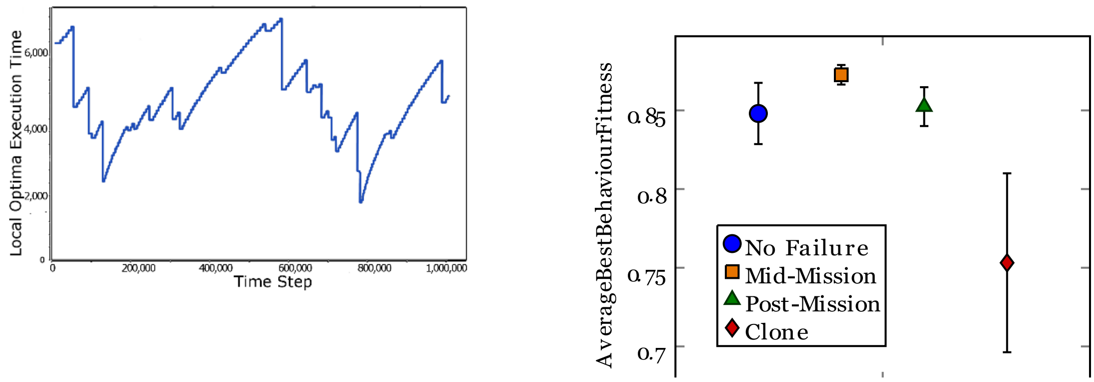
if !(target(Swarm_member, any_direction, furthest) has packet) or !(holding packets) **then**
collect packet from closest base

Mid-flight failure

The second set of testing shows not only that the introduction of unit losses has minimum effect on the delivery time, but also has a positive effect on the evolutionary process. For these tests, we would like to note our previous paper (Smith, Hunjet, Aleti & Barca, 2017) showed unit removal had a negative effect on the evolutionary process, and that Post-mission re-population outperformed Mid-mission re-population. These results have now been found to be incorrect, due to an error in re-population controls in the simulations. This paper presents the results produced after addressing said problem.

For most simulation instances the system was found to be resilient to minor losses; producing results similar to Figure 2a. However, in rare cases a major failure occurred due to specialised swarm members (see Algorithms 2 and 3) being lost. Figure 5a is an example of one such instance. As can be seen, the system is improving steadily for the first 100k steps. However, at 120k the specialised member is lost. This leads the system to fail, with small recoveries over the next 400k steps. At 600k the swarm evolution process has recovered from the loss, until 800k when a specialist is lost again. This shows that major failure of the swarm is recoverable by the HHE adjusting the swarm.

Figure 5b shows that, for the first two re-population methods, mid-mission and post-mission with new unit generation, the 90% confidence interval is improved, compared to the simulations without member failure, and the mean fitness is reduced for both methods: 0.5% for post-mission and 2.9% for mid-mission. This suggests that not only can the swarm continue to operate in smaller swarm sizes, but the increased random agent turn-over aids the evolutionary process.



(a) Example Evolution of Data Delivery Time

(b) Mean data delivery time and 90% confidence error margin for post-evolution rule-sets

Figure 5. Second test, exploring swarm units being removed and new units re-populating the swarm

The difference in data delivery time between the first two re-population methods can be attributed to mid-mission always having a swarm at full capacity, while post-mission must complete simulations with multiple agents lost. Therefore, the reduced swarm can be seen to take longer, with slower approaches, yet is still capable of completing the task.

The final test case, *Clone*, in which the lost agents' rule-sets are copied in the post-mission repopulation process, shows far worse results in both confidence range and mean best-evolved behaviour fitness. This is found to be due to the evolutionary process being negatively affected by the reintroduction of behaviours not fully explored in the simulation, resulting in invalid reuse in the next iteration. It can thus be seen, by comparing the two Post-mission re-population methods, that introduction of new, unknown rule-sets is preferred over the continued, unwarranted reuse of poorly performing agents.

Scalability

Figure 6a shows the evolved fitness of the swarm as its scale is increased (horizontal) and the distance of the bases is increased (vertical). These findings show the swarm is scaling effectively, with no noted reduction at large swarm sizes. That is, even with 30 agents operating in the smallest environment, the agents do not hinder one another's ability to aid in solving the task of data transfer.

In addition, it can be seen that in all swarm sizes explored, a gradual reduction in data transfer is observed, as all swarm sizes are evolving data ferrying behaviours where appropriate. Only when the distance becomes too great, relative to the swarm size, does a ferrying behaviour not evolve.

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This ability to evolve ferrying behaviours is further shown in Figure 6b, in which the theoretical relay behaviour fitness of (7) is compared. In all swarm scales, a positive (blue) comparison is observed in *s* values, which prevent pure relaying but allow evolved swarms to transfer via ferrying or ferry-relay hybrid behaviours.

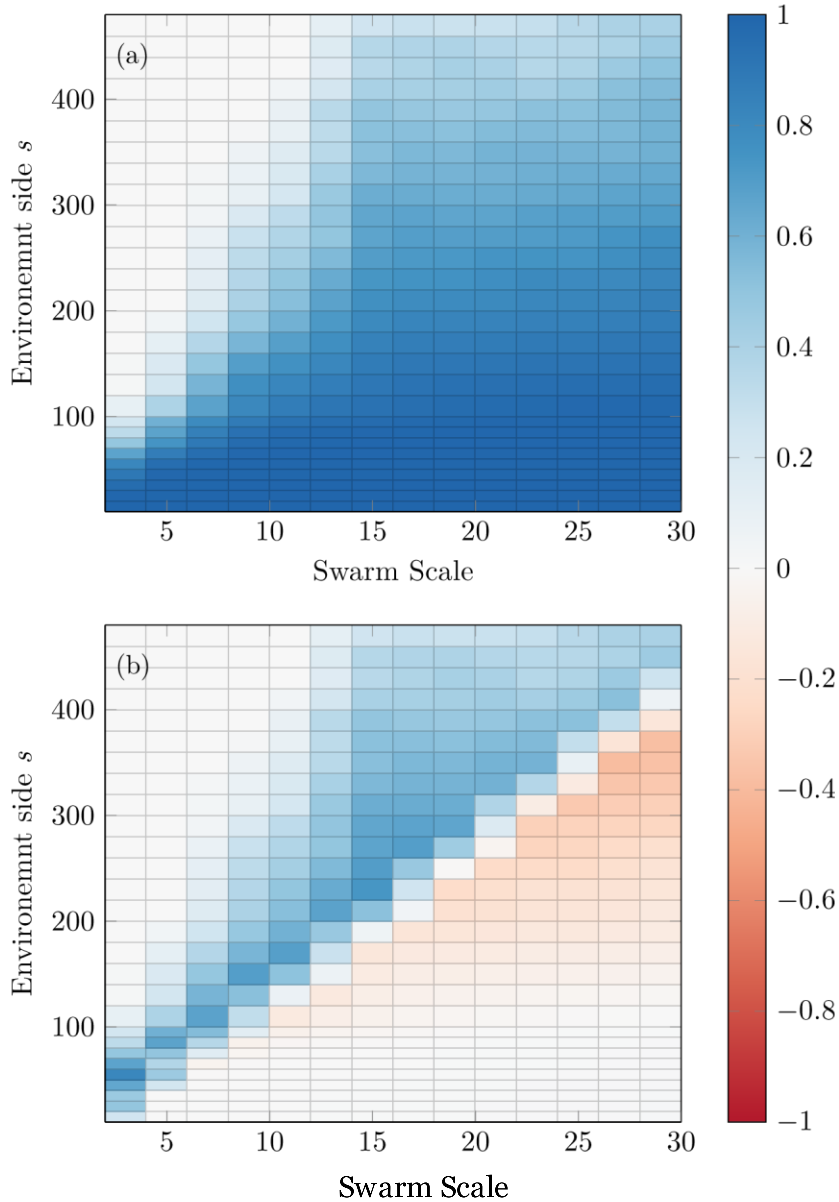

Figure 6. Scalability of swarm operations with 2-30 agents, in environments with side lengths and widths, s, 10-490. a) simulation fitness results, b) comparison of evolved behaviour and theoretical relay behaviour.

This figure also shows in operations with large Base Ranges, $s \geq 200$, in which the swarm may potentially evolve/learn relaying behaviour, swarm scale ≥ 20, the full relay is not being autonomously coordinated and the evolved behaviour is not achieving fitness values equal to the theoretical relay results. From this, and the prior observation of limited ferry behaviour range, it can be seen that the proposed autonomous evolving and learning swarm, although performing equally or better in most ranges, currently has limitations in the size of the environment in which it operates. This limitation may be due to a reduced evolutionary process, with T_{fail} set to 50,000 leading to only 20 generations explored. Further exploration is thus required with greater evolution allowances.

Learning contribution

The final exploration of this study is the comparison of the swarm with and without the online, learning process being implemented during the simulation.

In Figure 7 it can be seen that for small base ranges, 95, where basic relaying behaviours can be achieved, the learning process contributes little to the swarm, as basic relay behaviours are evolved. However, as the base range is increased, 113 and 128, relay-ferry hybrid or full ferry behaviours are required. This leads the non-learning swarm to have far lower fitness values. This indicates that the process of adjusting the swarm behaviour to meet the requirements of the environment is heavily reliant on the learning process, particularly when non-direct actions are required: that is, actions other than moving toward the sink device and transmitting packets in the direction of the sink device.

This exploration shows that for more complex environments, the inclusion of online learning greatly increases the ability of the swarm to appropriately explore potential behaviours and adjust accordingly.

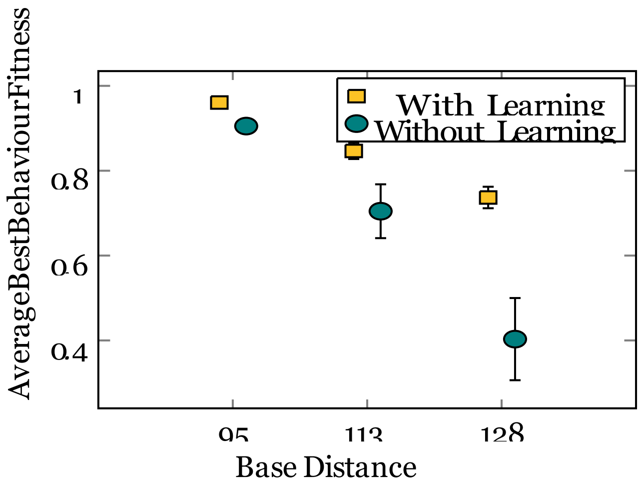

Figure 7. Comparison of Evolving with Learning vs only Evolving

Conclusion and Future Work

This paper has explored an online-learning, offline-evolving robotic swarm system to enable communications between disconnected network nodes. The approach was validated by testing in different environments, with different rule-generator seeds; it was found that this swarming system was able to adapt its *emergent behaviour* to effectively transmit data between a source and a sink node. Furthermore, Figure 2a and section *Learning contribution* show both the evolution and learning process are required for successful behaviour adoption. The swarming system is flexible, scalable and robust, evolving behaviours to best suit the environmental conditions and performing well even with the random removal of swarm members or with excessive swarm sizes.

The evolution method presented here replaces, or at least reduces, the manual heuristic development process previously required for swarm emergent behaviours to be created. This approach will thus allow a robotic swarm to be used in new environments, without expert heuristic engineers, and with a reduction in construction time. It will also allow the environment or the swarm to change between operations, with the HHE re-designing the rule-sets to maintain an effective swarm for the next operation.

Future work will introduce Gaussian variation to the propagation path loss of the communications environment, mobility to the source and sink nodes, and examine the effect on the solutions generated through variation of the cost penalties assigned to taking specific actions.

Acknowledgement

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Black Mountain Tower Canberra

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Abstract: Two historic papers from a special issue of the *Journal* in 1981 featuring the new Black Mountain telecommunications tower in Canberra.

Keywords: Telecommunications, History, Canberra, Black Mountain Tower.

Introduction

In 1981 the Society produced a special issue of the *Telecommunications Journal of Australia* (Volume 31 Number 2) featuring eight papers on the new Black Mountain telecommunications tower in Canberra. Two of these papers have been selected for this historic review.

The first paper (Taylor & Brigden, 1981) is an introduction to the construction of the tower and the vigorous protests against the project. The construction was debated by Planning Authorities and in Parliament by successive Governments and the associated environmental protests even reached the Supreme Court.

The second paper (Derrick, 1981) discusses the reasons for selecting the Black Mountain tower location and the long-term provisions therein for radio relay, FM and TV broadcasting, mobile radio, paging and other services.

The tower was opened to the public by Prime Minister Malcolm Fraser in May 1980 and has been a feature of the Canberra skyline ever since.

The other papers in that special issue of the *Journal* on the Black Mountain tower are highly recommended for further reading and cover the following topics:

- A Historical Review of the Planning of the Sydney–Canberra–Melbourne Trunk Route
- Project Development and Building Facilities
- Design and Construction
- National TV and FM Broadcasting Facilities
- Commercial Television Installation
- Buildings Engineering Services

Laurie Derrick (the author of the second paper) is still working in the Australian telecommunications industry and is accredited to provide Frequency Assignment Certificates

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in relation to Apparatus Licences and Interference Impact (and related certificates) for Spectrum Licences for the Australian Communications and Media Authority (ACMA).

Laurie confirmed an interesting anecdote regarding Black Mountain tower when I was researching this paper. Once electronic ignitions were first introduced to motor vehicles in Australia, it was possible to get stranded in the carpark at Black Mountain tower due the levels of RF radiation in the vicinity. The solution was to place a foil-backed space blanket over the dashboard and the car would start normally.

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The Historic Papers

The Telecommunications Tower, Canberra

The Black Mountain Tower — an Introduction

F. L. C. TAYLOR and W. F. BRIGDEN

The articles that follow will describe the construction of the tower, the facilities it provides, and explain why it was established on Black Mountain rather than on one of the many other sites that were suggested during the planning phase. It is sufficient in this introduction to say that Black Mountain was the only site that was truly suitable for both TV and radio telephone transmission, and was by far the most economic of all the alternatives considered.

Black Mountain is also a most sensitive part of the Canberra environment. It is a national park of considerable ecological interest containing unique flora and fauna, and the tower was clearly going to be a land mark which some people felt would dominate other aesthetic Canberra structures. With quite a number of people this feeling reached the point of outrage and vigorous protest against the project. Protests against the tower on aesthetic and ecological grounds were strongly voiced during the earlier stages of the approval procedures and at the various hearings which included a lengthy Supreme Court case.

Over a period, the emphasis of the objections against the tower gradually moved away from the ecology onto the visual and technological aspects. The Australian Post Office (henceforth referred to as Telecom) had little difficulty in disarming the accusations of faulty technology; e.g. you should not be planning interstate microwave systems because fibre optics will soon do the job better; you will get results just as good on other less elevated sites, on which the tower will be less prominent, etc. The question of visual impact was more subjective with a wide spectrum of public opinion, and finally this was the factor that most seriously threatened the project.

The tower saga started in April 1970 when Telecom asked the Department of Housing and Construction (H&C) to carry out a feasibility study in relation to a tower on Black Mountain, accommodating both communications services and facilities for visitors. Telecom and the Department of H & C presented the first tower proposal to the National Capital Development Commission (NCDC) in August 1970. The NCDC held a unique responsibility for the development of Canberra. Every new structure required their specific approval. The planning skill of the NCDC was reflected in the beauty of the City and their longstanding authority over the City development had never been seriously challenged. Thus the public clash which ultimately developed between Telecom and the NCDC over the tower design was an unfortunate affair for both parties. It was certainly the first time two major government authorities appeared before the Parliamentary Standing Committee on Public Works (PWC) in head-on contention. The events leading to this situation at the PWC hearing in June 1972 can be traced fairly briefly.

Following the submission of the first design (which was closely in accordance with the tower as it now stands) to the NCDC further alternative designs were prepared as a basis for discussion with the NCDC Advisory Committee. After the first round of discussions the Committee gave its support in principle to the design which included both the look-out and restaurant facilities. This was in December 1970.

However, NCDC was still uneasy about the aesthetics of the project and in April 1971 they proposed that the public facilities "drum" be deleted and replaced by an observation platform with spiral stairway access beneath the radio telephone (RT) "drum" at about 18 metres above ground level. Telecom indicated that this would seriously jeopardise the earning capacity of the tower and was not acceptable.

After further negotiation NCDC expressed the view that a tower with technical facilities only, presented the most satisfactory proposal. However; if the Government were to approve the Telecom proposal for added public facilities, they considered that the equivalent of one enclosed floor should be eliminated to reduce the impression of bulk at the visitor level. This effectively meant the elimination of the restaurant floor, and by this time, Telecom was becoming seriously concerned at the delay in reaching agreement.

Telecom finally stood by the view that the restaurant should be retained, having in mind that:

- After months of close consultation between Telecom and Department of Housing and Construction on the one hand, the NCDC and the National Capital Planning Committee on the other hand, there was substantial agreement. In practical terms, the only point finally in dispute was the question of inclusion or not of restaurant facilities on the tower. The NCDC stated its objection to this on aesthetic grounds.
- The Department of H & C and Telecom believed that the difference in aesthetic qualities between a tower with the restaurant and one without a restaurant was

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so marginal as to be insignificant when viewed from a distance.

- The inclusion of the restaurant would add prestige and, further strong interest in the other visitor facilities, all of which would improve Telecom's commercial position.

The proposal, including the disputed restaurant floor was submitted to Cabinet in October 1971 and Cabinet endorsed the technical aspects of the project for development to the stage where it would be ready for examination by the PWC.

In March 1972, NCDC issued a public statement which gave recognition to the importance of visitor aspects of the proposal, but indicated that NCDC was now of the view that the tower should be reduced in scope to that representing minimal technical facilities for television, radio and telecommunications.

The public hearing of evidence by the PWC took place in Canberra in June 1972. This was an unusually lengthy hearing with evidence being given by Telecom, Department of H & C, Australian Broadcasting Control Board, and Department of Interior. Other evidence was given by organisations which opposed the project on environmental or aesthetic grounds. Foremost amongst these was the NCDC which presented a quite new counter-proposal that television services be co-masted at Black Mountain and radio telephone services be provided on a tower at Mt. Crace. Telecom opposed the Mt. Crace proposal strongly on economic and other grounds.

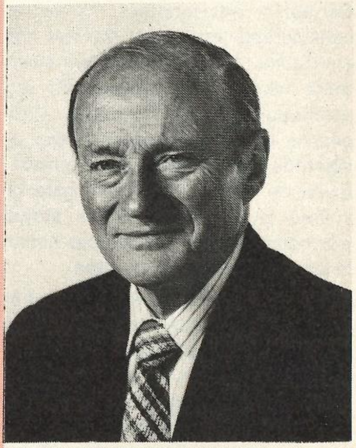
In August 1972 the PWC recommended to Parliament that construction proceed in accordance with the proposal as submitted by Telecom.

The Prime Minister of the day considered the proposal should be examined by his Ministers before it was debated in Parliament. A second Cabinet Submission had to be prepared. In September 1972 Cabinet endorsed the recommendation that the project proceed. The project was approved by the House of Representatives in October 1972, but Parliament was dissolved before the Senate debate was finalised.

On 5 February 1973 the Postmaster-General in the newly elected government requested the preparation of an Environmental Impact Statement. This statement went to Cabinet and was released by the Minister for Environment and Conservation on 28 February 1973. It attracted strong criticism from opponents of the project, much of which, in retrospect, was probably justified. However, this was the first Impact Statement to be

F. L. C. TAYLOR began as a Cadet Engineer in PMG in 1939 and rose to the top of the profession in Telecom to become General Manager Engineering, the position he held at retirement in 1980. During these 40 years he occupied a wide variety of engineering positions in Victoria, Queensland and at Headquarters. Additionally he did a tour of duty in London as Engineering Representative and also headed the APO in New South Wales as Director, Posts and Telegraphs. From Vesting Day he relieved as Chief General Manager for lengthy periods.

As SADG Programming Services he was the lead witness for PMG in the lengthy hearing into the Telcom Tower project by the Parliamentary Standing Committee on Public Works during 1972. He also appeared for the Department in the subsequent court cases as well as before the Parliamentary Labour Caucus in a debate with opponents to the Tower. The outcome of this virtually clinched the Government support to the project and paved the way for its construction.



W. F. BRIGDEN joined the PMG Department in Sydney as a Draftsman after returning from War Service in 1946. His subsequent studies in the Building Sciences and Real Estate Evaluation fitted him for service in the Buildings Branch where he worked through the various levels in NSW and Headquarters for 30 years, attaining the rank of Deputy Assistant Director-General. At Vesting Day he was appointed to his present position of Manager Programme and Projects Branch in the Buildings Sub-Division at Headquarters. For the past 20 years he has been directly associated with the designing and construction of every special major building erected for PMG/Telecom in the Commonwealth. He is the sole remaining Buildings Branch member who was involved from the earliest conceptual stages of the Telecom Tower in the 1960's through its developmental phases to completion in 1980.

presented to an Australian Government, and to meet the time commitment it was prepared by a small group of people over one week-end.

Tenders had been called in January 1973 and on 6 June 1973, a Letter of Acceptance was issued by Department of H & C to Concrete Constructions (Canberra) Pty. Ltd.

A few weeks later the Attorney-General advised the Postmaster-General of representations made by a group of fourteen prominent Canberra citizens seeking his fiat to an action to challenge the power of the Government to execute and carry out the construction of the tower.

The Attorney-General granted his fiat on 4 July 1973 to the institution of proceedings on behalf of these citizens seeking an injunction to restrain the construction of the tower on three grounds, namely, building on a public park, lack of NCDC approval, and that the tower would constitute a nuisance.

However, on 20 July 1973, Cabinet endorsed both the Black Mountain tower proposal and the Environmental Impact Statement. The approval of the Governor-General in Council was obtained on 19 September 1973.

After inter-locutory proceedings the case brought by the fourteen prominent citizens went to substantive hearing before the Supreme Court in Canberra. The hearing lasted some 4 weeks and traversed at length the environmental and ecological issues, and the authority of the Commonwealth to proceed with the work. In a judgment handed down on 31 October 1973 the Court rejected the arguments brought by the plaintiffs on environmental and ecological grounds, but found that as the Postmaster-General and the Minister for Housing and Construction did not have the approval of the NCDC a case for an injunction to stop the project proceeding had been established. The Court found that in every other way the Commonwealth was properly authorised, but on the issue of lack of NCDC approval, preliminary site works which had been going on for about a month ceased forthwith.

The Attorney-General lodged an appeal to the High Court against the Supreme Court finding in respect of the requirement for NCDC approval and this appeal was listed for hearing in May 1974.

In the meantime in December 1973 following the Supreme Court decision the Postmaster-General arranged for officers of this Commission to address a joint meeting of Caucus Committees and other interested Caucus members. The meeting was also addressed by a representative of the group who instituted The Supreme Court Action. Following this discussion which amounted to a debate between the Telecom representatives and the opponents of the project on the environmental, conservation, technological and economic aspects of the proposal, Cabinet agreed that the project should be implemented.

In the face of this further Cabinet decision the NCDC on 13 December 1973 gave unconditional approval to the project as approved by the PWC. This approval cleared the way for the project to go ahead and the Commonwealth did not proceed with the High Court Appeal. The Plaintiffs had lodged a cross-appeal against the Supreme Court finding that construction of the tower would be lawful (apart from the role of the NCDC). This was heard in May 1974 by the High Court and dismissed.

Thus after having been approved by the Parliamentary Works Committee after the longest hearing on record in August 1972, by Cabinet in September 1972, by the House of Representatives in October 1972, again by Cabinet in July 1973, by the Governor-General in Council in September 1973, and again by Cabinet in December 1973, and having been the subject of hearings in the Supreme Court and the High Court the project finally got under way in December 1973. With the Tower construction substantially completed by mid-1977, TV and FM broadcasting, and radiotelephone services were progressively installed and commissioned from that date. The Tower was finally completed and formally opened to the public in May 1980 by the Prime Minister of Australia.

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The Telecommunications Tower, Canberra

The Tower Radio Functions and Specification

L. J. DERRICK, B.E. (Elec.)

This article follows on from the introductory article and discusses in more detail the reasons for the tower being constructed and for the selection of the Black Mountain location. Also outlined are the technical specifications made for long-term requirements for radio relay, FM and TV broadcasting, mobile radio, radio paging and other services.

Some details are given of the accommodation requirements for internal plant and the associated antennas for the above services. The electrical and mechanical design criteria for the lattice steel antenna column, the tower lightning protection, and other details specified in the tower brief to allow for the continued orderly expansion of services when required in the future, are also discussed.

THE CASE FOR THE TOWER

As indicated in the introductory article, the planning of a telecommunications tower for Black Mountain, Canberra, began in earnest in April 1970. The events which led to this stage, however, began in 1964 when the then Australian Post Office was requested by the National Capital Development Commission (NCDC) in Canberra to examine the possible phasing out of the Red Hill radio relay station on aesthetic grounds.

The Red Hill station (**Fig. 1**) was the major Canberra terminal and repeater for microwave telephony and TV bearers on the Sydney — Canberra — Melbourne and Canberra — Cooma routes. The station consisted of a single storey brick building which housed the radio and power equipment, and a 39 metre lattice steel tower which supported the associated radio relay antennas. The NCDC felt that the tower should be removed as, in their view, it would detract from the view of the proposed new Houses of Parliament which were planned for establishment in the vicinity of Red Hill. As well as the aesthetic objections to the tower, future expansion on the microwave routes was limited in view of Department of Civil Aviation (now Department of Transport) restrictions on the height of the tower at Red Hill.

Many alternative sites for the Red Hill Station were considered subsequently, and eventually approximately twenty sites were selected for detailed study. Some of these are shown on the map **Fig. 2.** In each case the site was examined for suitability as a radio relay site and costs were estimated for establishment of the site including cost of power lines, roads, towers and coaxial cable connections to existing and proposed exchanges. Aesthetic and environmental factors were also taken into account. Hill top sites already established for other purposes were obviously of particular interest and one of these was Black Mountain. Black Mountain already had two separate establishments existing — the National television transmitting station and the Canberra Television Ltd. (CTC-7) television transmitting station and studio (**Fig. 3**). Accommodating the radio relay facilities on Black Mountain was shown to be significantly more economic than the establishment of another site. A road, power lines, coaxial cable route and other facilites already existed although additions and upgrading of some facilities would obviously be required.

The NCDC were advised that Black Mountain was the most suitable site for a combined TV and radio relay station and it was agreed that a study would be made of suitable structures to accommodate all requirements in a combined complex. The concept of a single aesthetically acceptable tower to provide for present and future TV, FM, radio relay and other radio requirements was, therefore, developed. The single tower solution was also favoured by the then Australian Broadcasting Control Board (ABCB) as it was expected to remove a TV reception problem. The existence of the two TV transmitting masts on Black Mountain had resulted in "ghosting" to TV reception in some parts of the service area because of mutual re-radiation of signals from the adjacent mast. Studies were carried out on many possible designs of towers in conjunction with the Commonwealth Department of Works (now Department of Housing and Construction). It was considered that the tower should provide facilities for all requirements for up to 50 years without any significant extension to the tower structure or associated buildings. The design of a number of existing and proposed overseas communications towers were examined as part of the study. The physical characteristics of some of these towers are summarised in **Fig. 4.** Finally in 1970, a tower

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design evolved which appeared to meet all requirements known and predicted and was flexible enough in design to cater for possible shifts in emphasis between the services. The tower has been constructed with very little modification to this original design.

THE SERVICES DESIGNED FOR

In view of the criterion mentioned above, which was to construct a tower suitable for requirements for up to 50 years, considerable thought was given to possible long term developments and requirements for radio relay, mobile radio and paging and TV/FM broadcasting. For the TV/FM broadcasting requirements, the appropriate planning body at the time, the ABCB was consulted.

Television Broadcasting

The ABCB specified that a minimum of 8 high power television services should be designed for with 4 in the VHF bands and 4 in the UHF bands. The VHF services were to be nominally of 100 kW effective radiated power (ERP) and the UHF — 1000 kW ERP. The VHF channel allocations originally specified were 3 (existing), 5, 7 (existing) and 9. In the UHF range, operation in any channels in BAND IV and BAND V was required. Later developments in FM broadcasting, however, resulted in Channel 5 not being available and the VHF channels allocated became channels 3, 7, 9 and 10 (see Table 1 for channel and band frequencies). In view of the closeness of some of the Canberra service areas to the Black Mountain site, the ABCB specified that the vertical antenna pattern should not fall below 7dB of the maximum down to a 10^0 depression angle.

As Canberra was developing in most azimuthal directions from the site, omnidirectional antenna horizontal patterns were appropriately called for. A minimum height of 122 m above the top of Black Mountain for the antennas was also a requirement.

The above specifications were believed to be appropriate for the design period for TV broadcasting for Commercial, National and possible Special and/or Educational Services.

TV Channel or BAND	Frequency MHz
CH 3 (VHF)	85 -92
CH 5 (VHF)	101 - 108
CH 7 (VHF)	181 - 188
CH 9 (VHF)	195 - 202
CH 10 (VHF)	208 - 215
TV BAND IV (UHF)	520 - 585
TV BAND V (UHF)	610 - 820
FM BAND (VHF)	88 - 108

Table 1 — TV and FM Frequencies

FM Broadcasting

The ABCB agreed that a minimum of 10 services of 10-20 kW ERP should be designed for. Although originally the frequency band of operation was specified as UHF, this was later modified to VHF after a decision was taken to revert to the international VHF band for FM broadcasting in Australia. A height for the antennas of 122 m nominal was specified.

As with the TV services, National, Commercial and possible Special/Educational services were to make up the 10 specified.

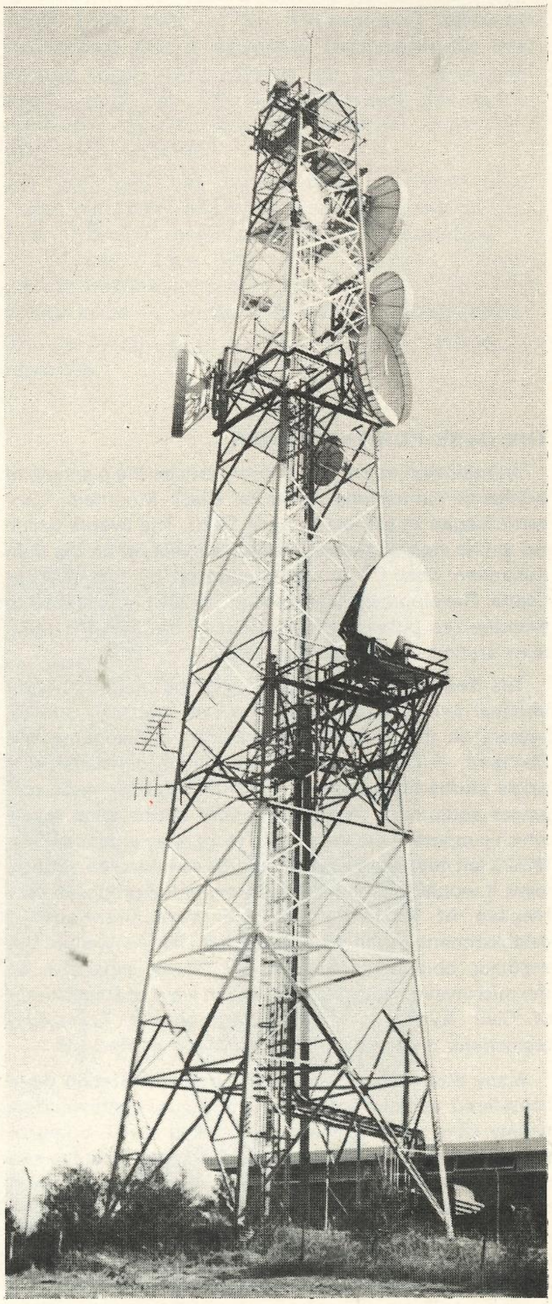


Fig. 1 — The Red Hill RT Station

Radio Relay

To cater for long term radio relay requirements it was decided to allow for full deployment of all the microwave bands between 2 and 15 GHz on the three main routes to Sydney, Melbourne and Cooma. Both telephony and TV bearers were to be accommodated. Path profiles were examined to the existing repeater sites and also to a number of other possible future repeater sites. Clearance of antennas above the site was specified to enable satisfactory transmission to all of these sites. A flexible antenna mounting arrangement was also required to enable transmission to be possible in any direction from the tower as requirements developed, in perhaps unpredictable directions. To achieve the above specification it was necessary to allow for 14 — 4 metre diameter dish antennas in each of the three directions, i.e. a total of 42. It was also thought necessary to cater for horn type antennas as alternatives. With operation in the higher frequency bands, close proximity of the equipment to the antennas was important to avoid excessive losses and intermodulation problems.

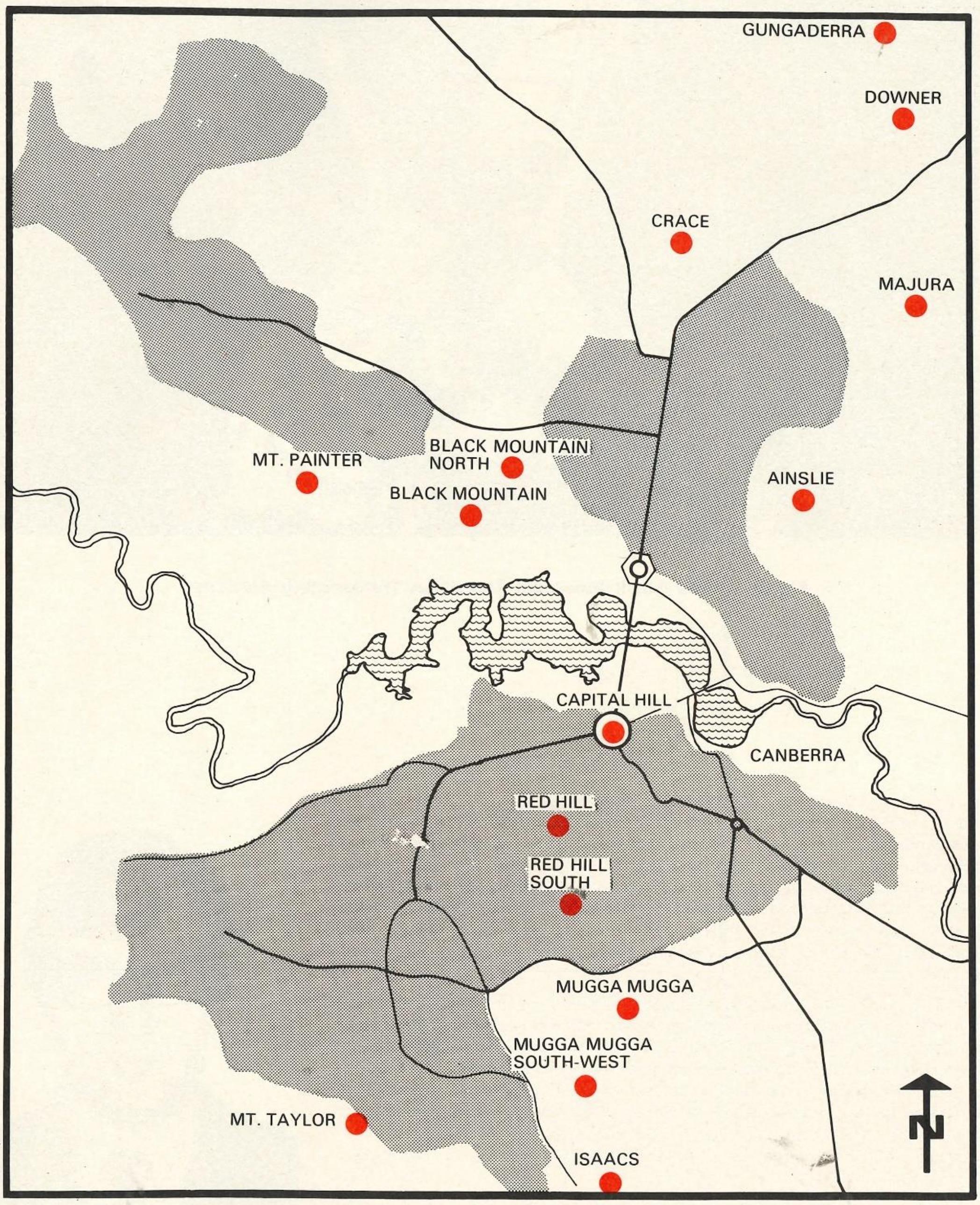


Fig. 2 — Alternative Sites Studied

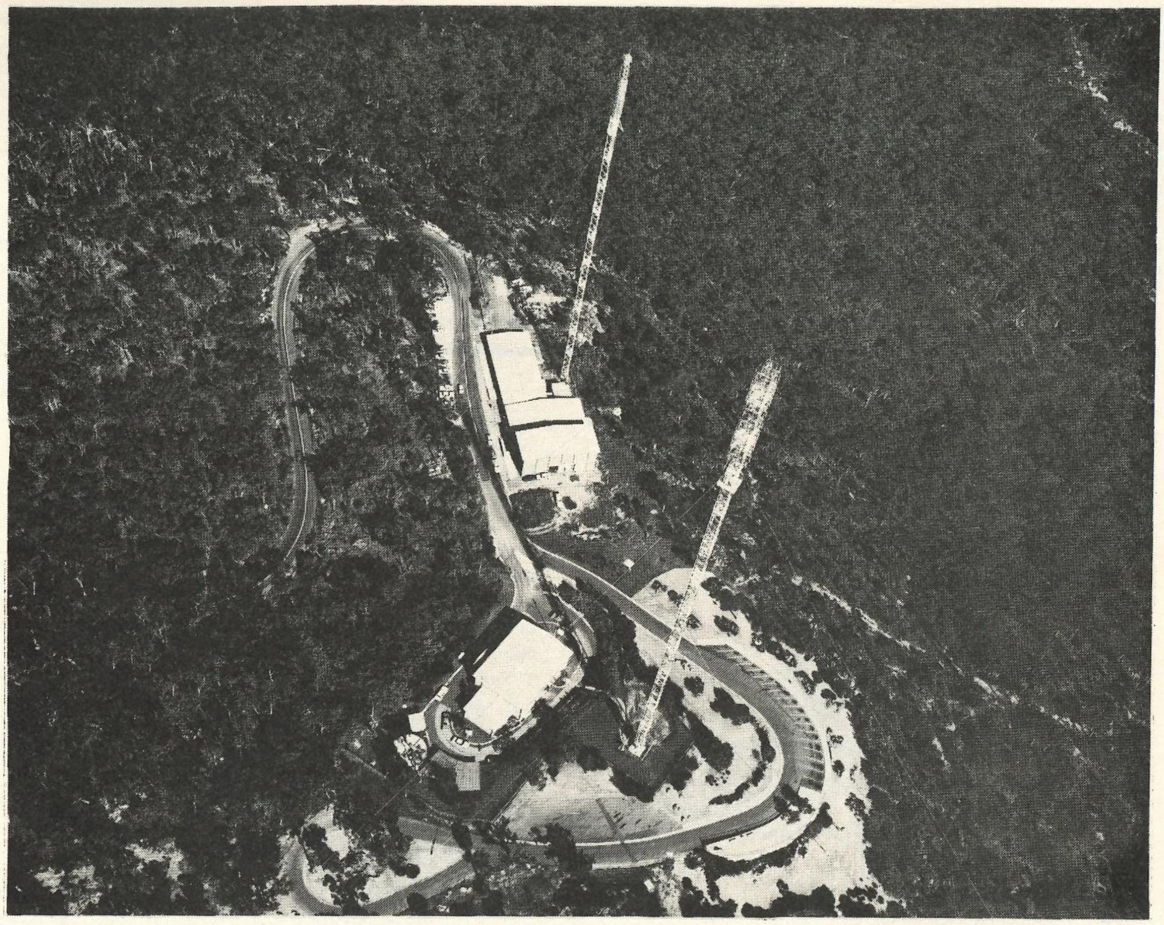
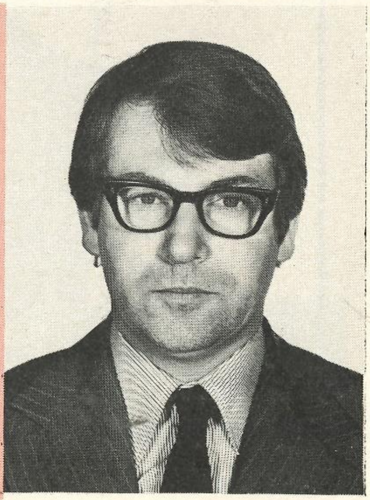


Fig. 3 — The Black Mountain Television Transmitting Stations

L. J. DERRICK completed a Bachelor of Engineering (Electrical) Degree at Melbourne University in 1961 and joined the Headquarters Radio Section of the Australian Post Office as an Engineer Class 1 in 1962. Since that time he has occupied a number of positions in the Broadcasting and Radiocommunications areas in the APO/Telecom Australia, and has worked on a number of large projects including the Radio Australia HF Broadcasting Station, Darwin, the Black Mountain Tower, Canberra, and the Public Automatic Mobile Telephone Service.

In 1971 he commenced work in a project team formed in the Radio Section to examine all broadcasting and radiocommunications aspects of the Black Mountain Tower Project, and in 1973 took up the Class 4 Engineer Project Leader position. His responsibilities included the identification and specification of long-term broadcasting and radiocommunication requirements and their impact on tower designs, the detailed design of the tower antenna column and the TV/FM transmitting antennas design and provision. In 1973 he gave evidence in the Supreme Court Case on objections raised to the tower construction.

He is currently the Staff Engineer Design Co-ordination Secretariat in the Design Sub-Division, Engineering Department, at Headquarters.



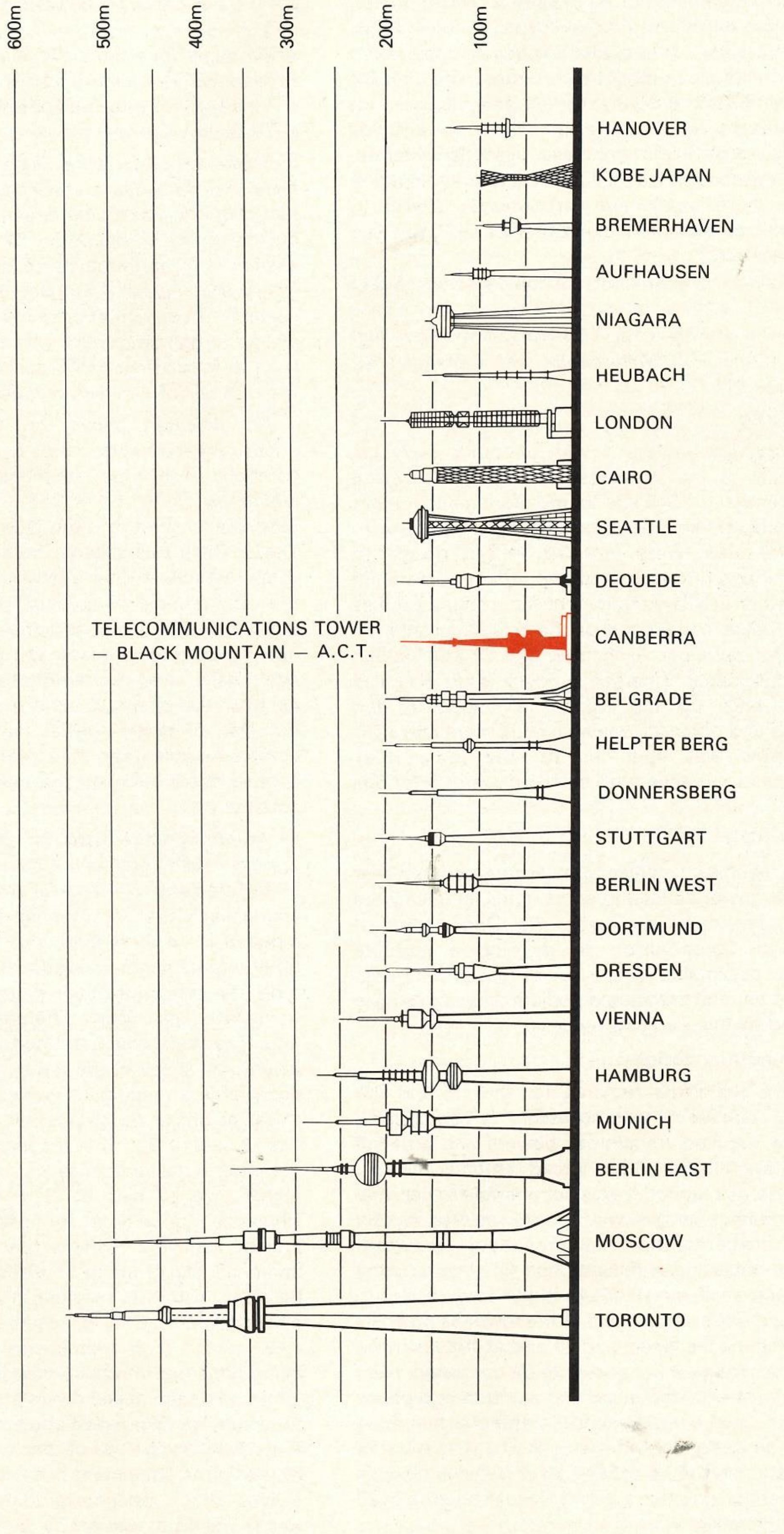


Fig. 4 — Some Overseas Towers

Mobile Radio and Paging

It became obvious after studying the requirements for all likely Government, semi-Government and Commercial mobile radio base station facilities, that all of Canberra's needs of this type could not be catered for in the tower. Limitations due to mutual interference problems and the difficulty of antenna accommodation became apparent. It was decided that accommodation for a total of about 80 services was feasible and 40 channels were allocated for APO (Telecom) services and 40 channels for Government, semi-Government and essential services. The Telecom allocation was to include a future telephone network connected public automatic mobile service. In the main, it was expected that 50 watt ERP services would be required.

Facilities were also required for the Telecom paging service.

Operation in the 80 MHz, 160 MHz, 450 MHz and eventually in the 900 MHz bands was envisaged for these services.

Other Services

Accommodation in the tower of other technical facilities such as for TV bearer switching (Television Operation Centre — TOC) and for monitoring and remote control of medium frequency broadcasting transmitters in the Canberra area, were included in the design to maximise the use of operational and maintenance staff. Of course, other ancillary equipment for systems such as the coaxial cable connection of the telephony and TV bearers to the telephone exchanges and TV studios had to be accommodated. Emergency power plant was also required to back up the AC mains supply to the broadcasting and other AC powered equipment and a DC battery supply was specified for the radio relay equipment, in accordance with standard practice for this equipment.

THE SOLUTION

With the technical facilities to be accommodated over the life of the tower defined in some detail, studies were carried out in conjunction with the Department of Housing and Construction to develop a suitable aesthetically acceptable single tower design. A large number of tower and associated podium building designs were studied in this iterative process.

Antenna Accommodation

To achieve the ERPs required for the TV and FM broadcasting services, it was necessary to compromise between the required transmitter powers and antenna gains. In view of the rather broad antenna vertical radiation patterns required it was not possible to use very high gain antennas as this would have resulted in very narrow vertical radiation patterns with resultant difficulties in achieving sufficient "null fill" down to the 10° depression angle specified. As it was also desired to minimise the cross-sectional size of the tower as much as possible to reduce the visual impact and as the antennas for the broadcasting services were to be comasted, each antenna had to be limited in vertical aperture and hence gain to enable a structurally feasible antenna mounting structure to be designed. In view of the large number of TV and FM channels to be catered for, it became obvious that multichannel antenna systems should be employed as much as possible.

Starting from the minimum specified height for the TV/FM antennas of 122 m above the Black Mountain summit, the solution adopted was to design for four stacked antenna systems as follows:

- TV Band II (channels 3 and 5 later changed to channel 3 + FM)
- TV Band III (channels 7 and 9 later changed to channels 7, 9 and 10).
- TV Band IV (up to 4 channels)
- TV Band V (up to 4 channels)

These antennas were designed to be mounted on a square cross-section lattice steel antenna column with reducing cross-sectional dimensions with increasing frequency band of operation to allow optimum antenna designs and performance to be achieved. The antenna systems comprise a number of levels of four radiating "panels" — one on each of the four faces of the antenna column. Additional space was allowed for on the antenna column for another FM broadcasting antenna in view of the number of services proposed for the long term.

As indicated above, for full deployment of the microwave frequency bands between 2 and 15 GHz, 14 parabolic dish type antennas in each of the three directions would be required. It was also considered desirable to allow for horn type antennas as alternatives. The possible use of other multiband antennas was also examined where their use would result in a reduction in the total number of antennas required. Although a few designs of this type of antenna existed at the time, it was not considered prudent to rely on their long term availability and suitability and, therefore, a total complement of single band dish antennas was allowed for. Use of these special multiband antennnas is, of course, feasible if required in the future and would result in more space being made available for other minor route antennas.

Various arrangements for the accommodation of 42 parabolic dish antennas (3 directions — 14 in each) of 4 metre diameter were considered. It was realised that it was unlikely that all antennas of this diameter would be required in all three directions, however there would be other requirements for small capacity system antennas in other directions for minor systems such as TV studio to transmitter links. Many different configurations of the 42 antennas were examined and the impacts on the total height and shape of the tower were estimated. The most acceptable arrangement arrived at, reducing the overall tower height as far as possible, was to group 36 antennas (3 sets of 3 x 4) in a compact volume. Mounting of the other 6 dish antennas was designed for at a separate higher level (3 sets of 2) to allow for adequate path clearance requirements for possible 2 GHz systems or to provide sufficient diversity spacing from the bulk of the antennas. The group of 36 dishes with suitable clearance between dish rims resulted in a volume about 30 m in diameter and 12 m in height existing behind them. In view of the high frequencies of operation eventually being required, to reduce possible waveguide losses and intermodulation noise, it was considered highly desirable to locate the microwave equipment in close proximity to the antennas. The use of the volume behind the group of dishes for an equipment housing therefore evolved and a 3-floor "drum" design eventuated. The height of the bottom of the drum was set by the minimum antenna height

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to give satisfactory radio path clearance to existing and possible repeater sites allowing for some growth of the trees on the Black Mountain summit.

Having set the level of the bottom of the RT drum at 30.5 m and allowing for the drum height, the height of a "public" drum and the mounting of the additional 6 dish antennas on another simple platform, the space between 80.8 m and the TV/FM antenna column base level of 132.3 m was examined for its suitability to accommodate additional antenna systems for mobile radio, paging and additional future FM broadcasting services. Studies of a number of possible antenna configurations and transmitter combining systems for mobile and paging services requiring omnidirectional cover from the tower were carried out. It was determined that there was sufficient space available in this region for the required number of antenna systems composed of 2 dipole units, one on each side of the tower to cater for the requirements. Mounting arrangements on the shaft and suitable weatherproof penetrations for cables were specified to accommodate these antennas and their associated cables.

Television Outside Broadcast (OB) antennas were allowed for on a dish platform above the 6 radio relay antennas, and on the RT drum while antenna space was not required for the fixed microwave systems. Finally, an allowance was made for possible mobile/paging antennas on the top of the lattice steel antenna column.

Thus the full complement of antennas for all radio services likely to be required in the lifetime of the tower was taken into consideration in the tower design. The arrangement for antennas was chosen to be flexible to allow for operation in different frequency bands, different direction of transmission and took into account possible shift in emphasis, e.g. less antennas required on the main Sydney, Melbourne and Cooma routes and more on minor routes in unpredictable directions from the tower. The design was also sufficiently flexible to enable broadcast antenna space to be used for mobile radio and paging services if required or vice versa.

Internal Plant Accommodation

As mentioned above, the volume enclosed by the main group of radio-relay antennas was utilised for an equipment housing for the radio-relay equipment allowing short wave-guide connections from the equipment to their associated antennas. The volume available for the equipment drum was sufficient to allow a three floor design.

Based on the size of modern microwave equipment and ancillaries such as battery supplies and line equipment, one floor could accommodate the fully expanded microwave needs. The use of the additional two floors for mobile, paging, broadcast monitoring, maintenance, T.O.C. and other functions then became a logical step.

A podium building was incorporated in the design to house the rather high power (and hence high volume and weight) TV and FM transmitters. The building was designed to accommodate the following transmitters estimated to be the maximum requirement during the proposed life of the tower:

VHF TV 2 x 10 kW (parallel, air cooled)— 4 installations

UHF TV 2 x 30 kW (parallel, vapour cooled)— 4 installations

VHF FM 10 kW (air cooled) — 10 installations

Floor layouts and installation techniques proposed were chosen to allow for maximum flexibility in the choice of the type and size of transmitters. A "one floor" transmitter installation was adopted and attention was given to the progressive installation of transmitters and the need for electrical connections, cooling requirements and antenna feeder runs to the tower cable riser. It was decided to draw cooling air for the air cooled transmitters and for the heat exchangers for the vapour cooled transmitters through perforated walls on the outside of the building. The cooling fans, heat exchangers, other pumps and noisy rotating machines associated with the transmitters were specified to be located in partitioned rooms adjacent to the outer perforated walls to reduce internal building noise levels. The cooling air from the transmitting plant was specified to be discharged through the building roof to reduce the mixing of hot discharged air with the input cooling air. The cooling air outlets in the roof consisted of aesthetic cowl units which blended with the roof surrounds and were flanged on the inside to connect to the ducting runs from the transmitters.

A TV/FM control room was specified to house programme input equipment, test and monitoring equipment and control desks. It was envisaged that all TV and FM transmitters would be controlled and monitored from this central location on the transmitter floor. The transmitters could also be operated and monitored remotely in the RT drum if this became a more efficient arrangement in the future with the integration of staff on other operational/monitoring duties with the ground floor broadcasting staff.

Store and maintenance areas were specified in the RT drum for maintenance requirements for the radio telephone and ancillary services and in the ground floor area for broadcasting services. A separate store to hold and allow handling of the large transmitting tubes for the TV and FM transmitters was also included in the specification for the ground floor area.

The Resultant Tower Design

Comasting of the main TV/FM broadcasting antennas and a mobile/paging antenna produced a requirement for an antenna column of 63.1 m in height. As these antennas were specified to be a minimum of 122 m above the Black Mountain summit, a tower height of 195.2 m resulted, allowing for the drop in level of the tower site from the summit.

The selection of a tower design of reinforced concrete up to the antenna column level solved the problem of minimising the deflection of the antennas on the antenna column due to wind loading, as discussed in the next section.

With the basic user specification set, as mentioned previously, the Department of Housing & Construction architects produced many alternative tower designs. Eventually the design of the now constructed tower (**Fig. 5**) emerged after many iterations where the functional, aesthetic and environmental merits of each proposal were exhaustively studied. Before the design was finalised, other related aspects which impacted on the design were taken into account. Antenna installation methods, antenna feeder cable runs and installation methods, coaxial cable requirements, DC and AC power leads, lifting methods (catheads, cranes and winches), interfloor cabling and aircraft warning lighting installations were some of these aspects, which were examined in detail and had significant influences on the detailing of the tower.

DETAILS OF THE DESIGN OF INTEREST

Antenna Column

Because of the interaction of the electrical design of the TV/FM transmitting antennas with the dimensional/structural design of the antenna column, the design and detailing of the column was carried out by the APO/Telecom for inclusion in the tower tender documentation. The required comasting of a number of antenna systems with the electrical requirement to have a decreasing maximum cross-sectional size of column with increasing frequency band of operation resulted in a need for a long and fairly slender structure. As deflection of the antenna column as a result of wind or uneven solar heating would cause the antennas horizontal beams to tilt causing unsatisfactory reception in the distant parts of the service area, the following maximum tolerable deflections were specified:

	100 kph Wind	Solar Heating
UHF TV Antenna Systems	$\pm 1.0^{\circ}$	$\pm 0.65^{\circ}$
VHF TV/FM Antenna Systems Band 3	$\pm 2.2^{\circ}$	$\pm 1.3^{\circ}$
Band 2	$\pm 3.2^{\circ}$	$\pm 1.0^{\circ}$

The maximum tolerable deflections are set by the maximum gain and hence the narrowness of the vertical radiation pattern of each antenna system likely to be installed on the antenna column. The 100 kph wind level was based on the small percentage of the time the wind would exceed this speed on Black Mountain.

A higher tolerance was placed on the deflection of the column due to solar heating because it is a relatively long term steady deflection whereas the wind deflection is a short duration effect and would occur only when the wind speed gusts to the 100 kph level. These specifications refer to the total tower performance and for the wind loaded case mainly relate to the antenna column deflection as the concrete section of the tower would have an insigificant deflection in winds of this speed. For the solar heating, however, the main contribution to the movement would be in the concrete shaft due to the elongation of the side facing the sun and the relatively poor concrete thermal conductivity. The structural design of the antenna column, therefore, was governed by the wind deflection criteria.

The column design adopted used the standard bolted galvanised angle iron construction of radio relay radio towers. In view of the length and relative slenderness of the column the windloaded column deflection (rather than strength of the individual members) became the limiting design factor and a very heavy design resulted. The leg members at the top of the concrete shaft utilised four 8" x 8" x 1" (203 x 203 x 25mm) angle iron sections back to back per leg. For one of the transition sections where the column tapered to a small cross-sectional area plate members 25.4 mm thick were designed in view of strength requirements and the limited space available inside the column for access and cable and antenna feed system installation. As wind induced vibration of this slender column was expected, special lock nuts were specified to prevent the standard tower nuts from becoming loose. Both high tensile and mild steel members were used in the design and in view of the low temperature conditions experienced in Canberra, steel with suitable notch ductility at 0°C was specified.

For each antenna system the back to back spacing of the radiating panels had to be kept within a maximum specification for suitable horizontal radiating patterns to be achieved. In view of the relatively heavy construction required to achieve the wind deflection criteria, considerable attention had to be given to the detailing of the design to avoid a larger than optimum cross-sectional dimensions while allowing sufficient effective space inside the column for cables, feed systems and access. A portion of one of the detailed antenna column drawings is reproduced in Fig. 6.

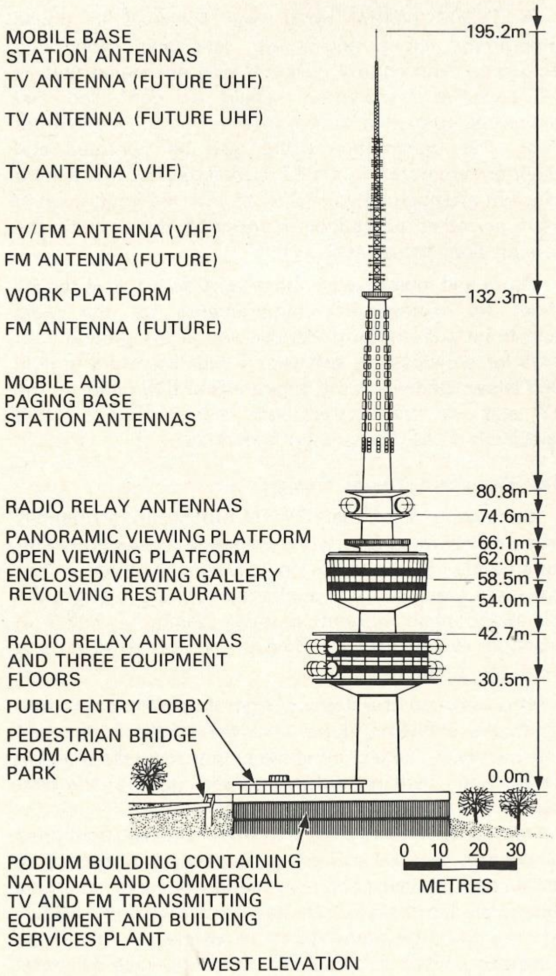

Fig. 5 — The New Tower Outline

In view of the narrowness of the column and the large number and size of the feeder cables which would eventually run through the column, and the feed distribution systems to be installed for each antenna system, a flexible runway system was incorporated in the design. Cable positions on this runway were reserved for the large diameter cable to avoid installation problems in the future. The runway was also designed to take power cables for aircraft obstruction lights, and hazard beacons and for other purposes.

The column was designed for wind deflection and strength on a static basis and it was considered that dynamic calculations should be carried out to confirm the satisfactory performance of the total concrete tower/steel antenna column system in the gusting winds which would be experienced in practice. The Department of Housing & Construction commissioned a detailed study of the dynamics of the system and confirmed that the deflections in both the down wind and transverse wind directions (due to vortex shedding) would be within the specifications for an acceptable percentage of time.

Antenna Feeder Cable Requirements

It was realised that there could be considerable difficulty in installing the large diameter antenna feeder cables from the TV/FM broadcasting transmitters when additional services were required in the future due to restricted space in the tower core and the antenna column. The usual practice was to feed each antenna

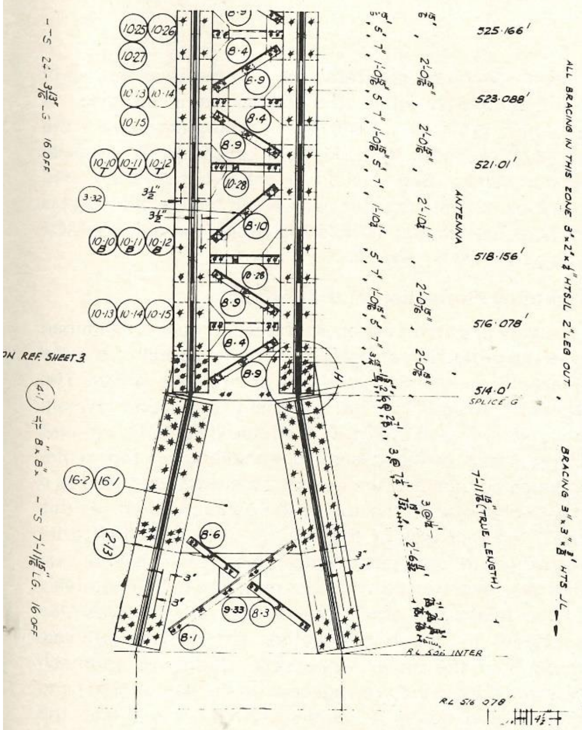

Fig. 6 — Portion of Antenna Column — Detail

with two cables and in view of the length of the runs and frequencies of operation in the UHF band cables up to 6¹/₈" (156 mm) in diameter were envisaged. Cable layouts and installation techniques were specified on the basis of the following plastic jacketed corrugated outer coaxial cables:

4 x 6¹/₈" (156 mm) for UHF TV
4 x 3¹/₈" (79 mm) for VHF TV/FM
4 x 3¹/₈" (79 mm) for FM
1⁵/₈" (41 mm) & ⁷/₈" (22 mm) for Mobile Radio and Paging

The most difficult operation was seen as the later installation of the 6¹/₈" (156 mm) diameter cables in view of their large bending radius, size and weight. The underground cable tunnel was dimensioned and positioned in the design to be suitable for the installation of these cables. This tunnel was designed to join the cable riser in the tower shaft which was to run from the sub-basement level to the top of the concrete shaft. The installation technique designed for was to use a winch at ground level near the entrance manhole to the cable tunnel and haul the cable from its drum down the tunnel manhole and up the riser to the required level in the antenna column. A lifting arrangement designed for location at the 132.3 m platform level was used in this operation (and also to lift dish antennas). The lower end of the cable would terminate at the ground floor level of the shaft and join with rigid coaxial line which penetrated the shaft above the false ceiling level in the transmitter hall and which would run horizontally to the transmitter cubicles inside the false ceiling.

For the runs from the microwave equipment to their associated parabolic dish antennas, flexible corrugated plastic jacketed elliptical waveguide was adopted. These waveguides were designed to run in a false ceiling in the RT drum, through a penetration unit in the drum wall and along runways on the outer drum wall to the appropriate antenna position.

It had been noticed in some overseas towers that there was a problem where cables had to be subsequently installed through the concrete tower shaft or through floor slabs and building walls. These penetrations often had to be fire rated and weatherproof and ideally should have allowed speedy and orderly installation as required during the life of the tower. A number of possible solutions were examined and eventually an existing commercially available system was adopted — the multicable transit (MCT) frame. This consisted of a cast-in steel frame which was fitted with modular silicon rubber blocks either solid or in two halves, with an appropriate sized hole in them to seal the cable to be installed. The frame included components to clamp the rubber blocks tightly together to seal the penetrating cables to the blocks and the blocks to the frame. At any time a cable was to be installed the frame clamp/screw could be loosened, a solid-block removed and replaced with one of suitable size to seal the cable. A large number of these frames were specified for installation throughout the tower, — in the tower shaft to the outside for antenna cables, in the floor slabs and walls of the RT drum and podium building and at the top platform of the tower where the antenna column commenced. It was discovered in some of the earlier towers overseas that there was insufficient provision for cable penetrations with resulting later problems of cutting through the

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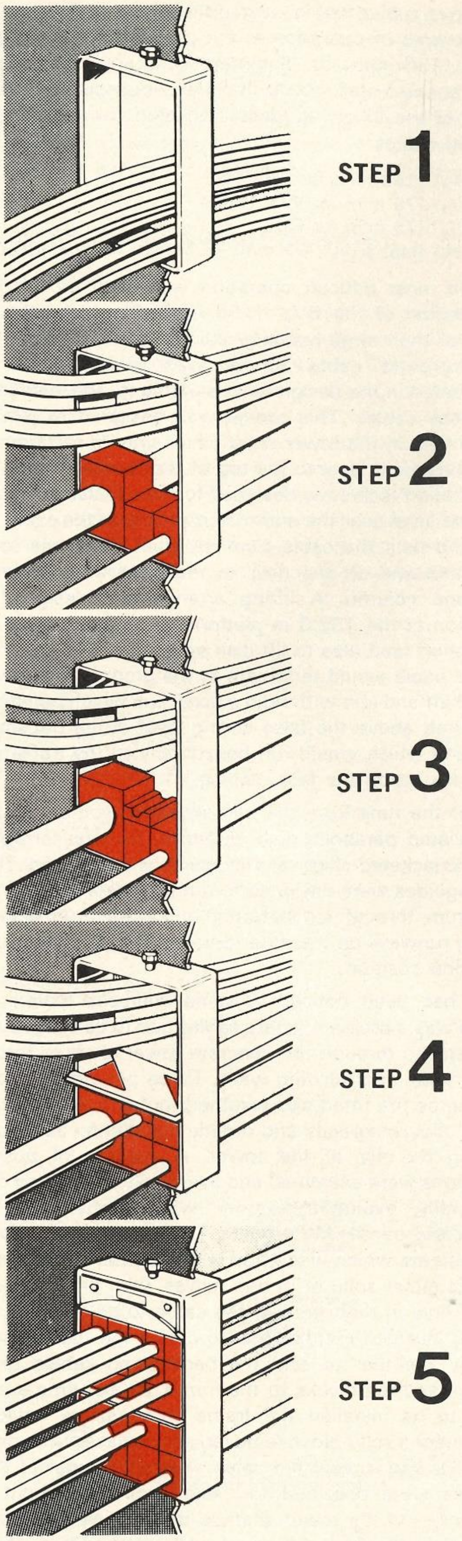

Fig. 7 — Multicable Transit (MCT) Unit — Cable Installation

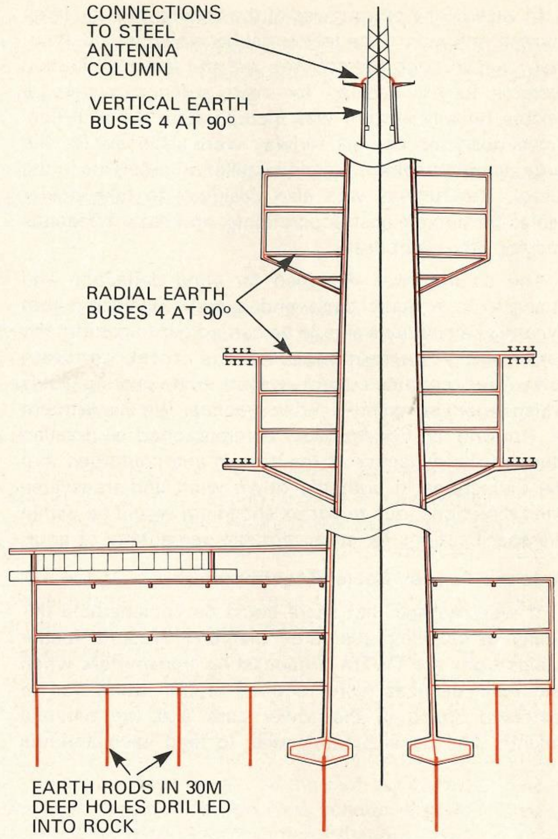

Fig. 8 — Lightning Protection System

heavily reinforced concrete and with the later sealing of the penetration when the cables were installed. A generous provision of the MCT frames throughout the tower is expected to avoid these problems. The special rubber blocks used expand in the event of a fire and continue to seal the cable even when the plastic jacket is melted. The method of installing cables through the MCT unit is shown in **Fig. 7**.

Lightning Protection and Earthing

A very important aspect of the tower design examined was the protection of personnel and equipment from the effects of a lightning strike to or near the tower. The general principle of the lightning protection system adopted is shown in **Fig. 8.** A standard lightning rod was incorporated in the design for mounting on top of the antenna column and the column steelwork was used as a downconductor to the top of the concrete shaft. At this point the four legs of the column were specified to be connected to four steel downconductors which were cast into the concrete and which were tied at regular intervals to the reinforcing steel. The reinforcing steel was also specified to be tied together at regular intervals throughout the tower. A possible alternative approach was considered but was rejected on the basis of cost and degree of difficulty in carrying it out — this was the welding of groups of the vertical reinforcing steel together to form downconductors. All metal components in the tower of significant size were specified to be connected to the four vertical downconductors. Four radial conductors were designed to run from the shaft vertical runs to the extremities of the public and RT drums in each floor and roof slab. These connect to the reinforcing in wall columns, the antenna mounting rails, window frames and other metal components. Internal to the shaft the steel ladderway, cable trays and other large metal fittings were also connected to the downconductors. The arrangement at the RT and public drums in effect produces a faraday cage which would protect people and equipment inside.

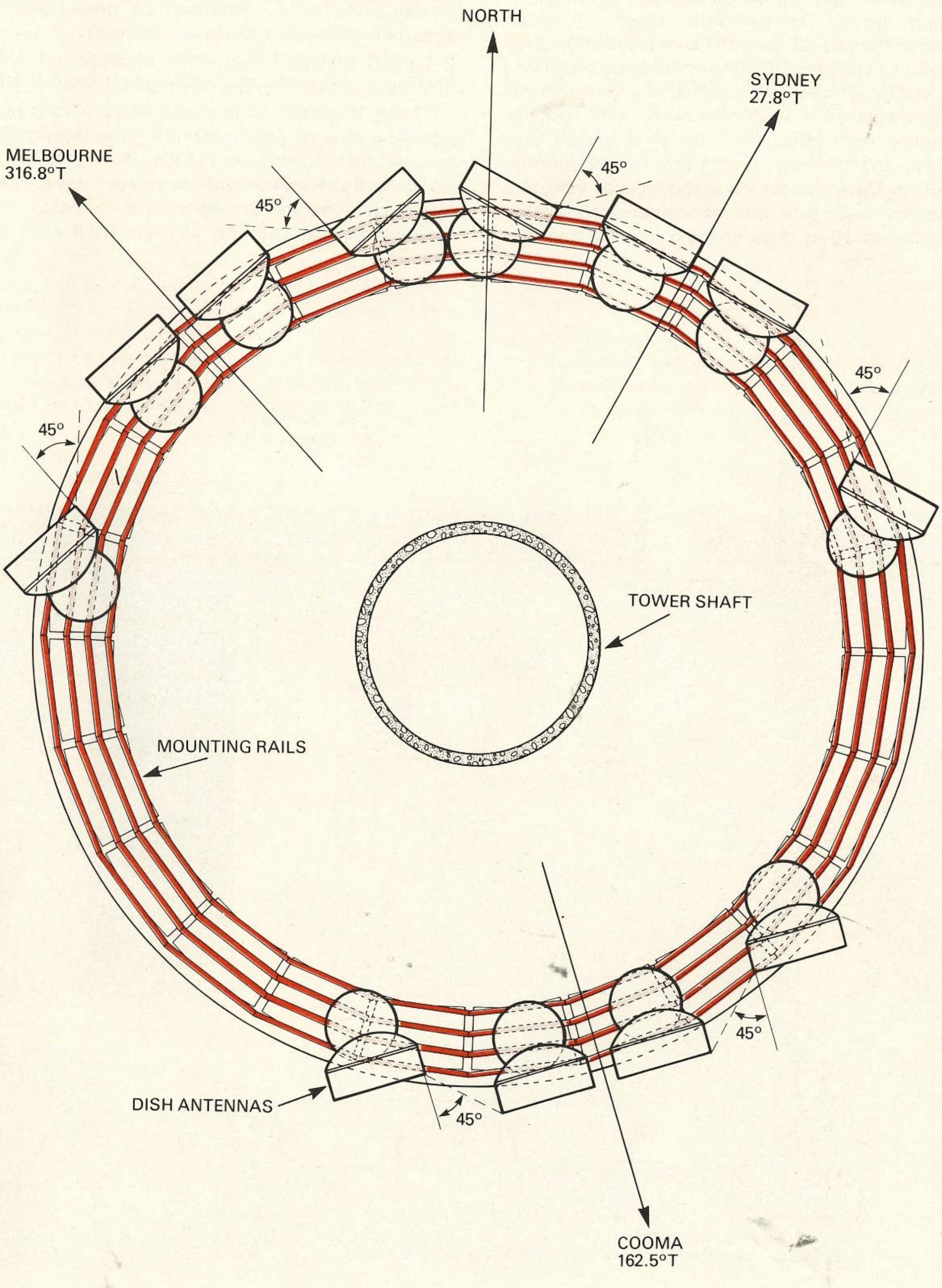

Fig. 9 — Parabolic Antenna Mounting System — Plan

The above philosophy was also applied in the podium building where horizontal runs of steel conductors in the concrete slabs were specified which connected the wire tied reinforcing rod and other components to the main vertical conductors. Tags from these vertical and horizontal conductors were specified to penetrate the concrete surface at intervals to allow earthing of installed equipment as required.

The tower reinforced concrete foundation also had a number of steel lightning conductor runs specified for installation around its perimeter (cast in) which connected to the vertical runs. The downconductors then terminated in a combined power and lightning protection earthing system which was composed of a large number of conductors placed in 30 m deep bores in the rock under the tower shaft foundation, the lower ground floor building slab and elsewhere on the site. The conductivity of the rock on Black Mountain was shown to be very pocr from site measurements and necessitated the rather large number of 30 m deep earthing rods to meet the earthing resistance specification. For lightning purposes, an earthing resistance of less than 10 ohms was required with a desirable target of 2 ohms. The power earthing for the sub-station in the tower was specified at 1 ohm, however, and this then became the target. All reinforcing in walkways, roadways, cable tunnel, water tanks, etc. and coaxial cable ducts, water and sewer pipes, were specified to be connected together and to the tower earthing. Some service pipes which used rubber sealing joints were also specified to be made electrically continuous with straps. Attention to these details was important to guard against the possibility of anyone on site being subjected to excessive step potential or side flashing in the event of a lightning strike to the tower.

The earthing rods to be placed in the 30 m bores were specified to be of galvanised steel to be compatible with the steel downconductors and the steel reinforcing, coaxial cable ducts, water and sewerage pipes. This was expected to reduce any electrolytic corrosion of these facilities or the earthing system itself. The power

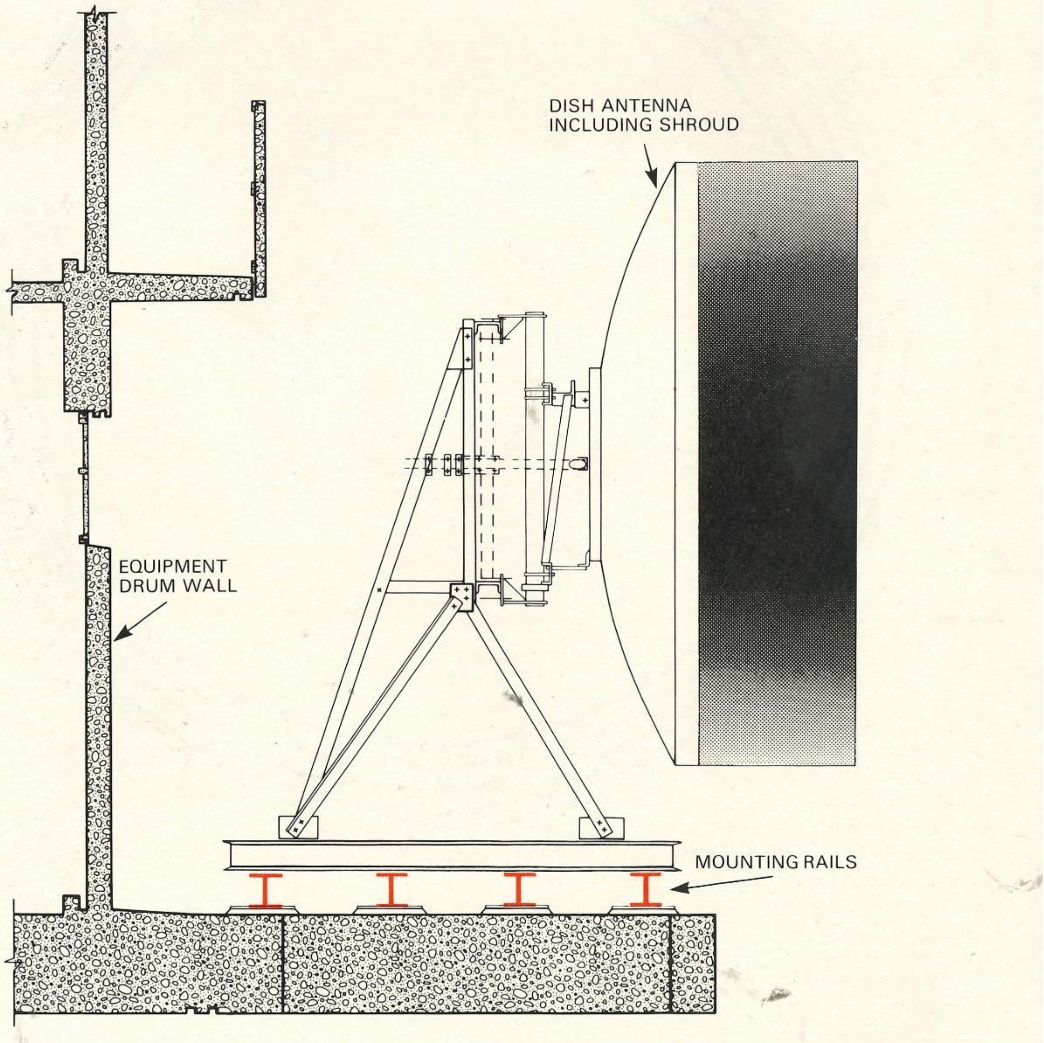

Fig. 10 — Parabolic Antenna Mounting System — Elevation

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authority, however, insisted on copper being used for the rods in view of their experience of galvanised earthing systems measuring high in resistance after some time.

As there is always a possibility that lightning could strike lower down on the tower and not at the top, an outside conducting band on the highest parts of the podium building roof was specified to be connected to the downconductor system. The steel safety fence on the public drum and the antenna mounting rails on the RT drum would similarly protect those areas.

Microwave Antenna Mounting Arrangements

A flexible mounting arrangement was required for the installation of parabolic, horn or other multiband antenna systems on the RT drum and dish platform. The requirement was to accommodate antennas of varying sizes without restricting any direction of transmission. The spacing between the RT drum floor and roof was chosen to allow the installation of two levels of the largest parabolic dish size (4 m) or a single level of horn type antennas.

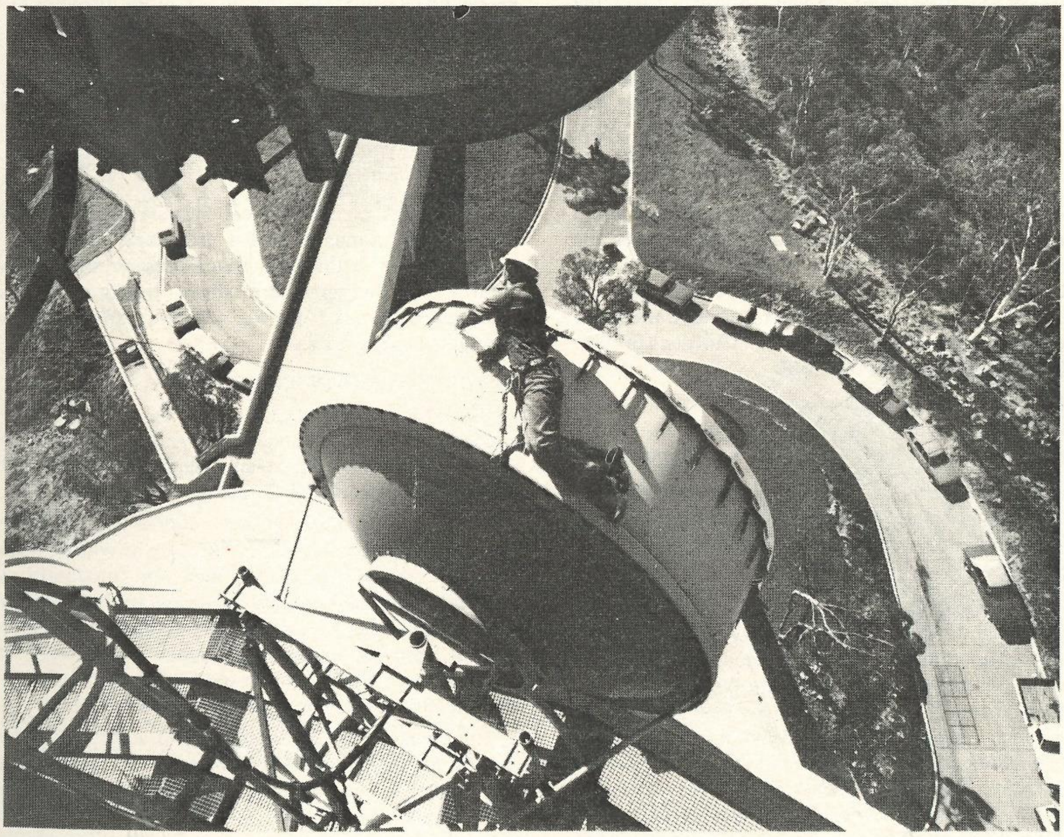
A rail mounting system was devised which gave the required flexibility. Four concentric rails were specified to be installed at the three levels of the RT drum. The antennas were to be mounted on individual mounting frames with ring beam bases and these mounting frames with dishes attached would then be clamped to the rails in any required position or orientation. This system is shown in plan and elevation in **Figs. 9 and 10.** At the lower and upper RT drum levels the mounting frames are placed on top of the rails whereas at the second level the mounting frames hang from underneath. The frames have been designed to mount antennas of varying size and the design was based on the use of the usual dish mounting arrangement for standard radio relay towers.

CONCLUSION

This article has outlined the main broadcasting and radiocommunication requirements which influenced the design of the tower and its location. Antenna, transmitting equipment and ancillaries accommodation specifications, which formed part of the brief to the then Department of Works are also discussed.

Other articles in this issue discuss the construction of the tower and the installation of the broadcasting and radiocommunication equipment in it, and indicate that little departure was necessary from the originally specified tower design or from the accommodation arrangements adopted in the design.

As additional services are required in the future, it is expected that they will be efficiently accommodated in the tower without the need to extend or significantly modify the podium building or tower proper.



Installation of Radio Relay Dish Antenna on RT Drum

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An Energy Efficient Receiver-based Flooding Scheme Using 1-Hop Neighbours Geographical Information for MANETs

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Abstract: Flooding is a fundamental, critical, and indispensable operation to support various applications and protocols in wireless ad hoc networks. The traditional flooding scheme generates excessive redundant packet retransmissions, causing contention and packet collisions, and ultimately wasting limited bandwidth and energy. Some recent flooding schemes that avoid those problems have been studied. They can achieve local optimality and have lower computational complexity. However, drawbacks limit the efficiency of these schemes. In this paper, we propose an efficient flooding protocol that minimizes flooding traffic, leveraging location information of 1-hop neighbour nodes. Our scheme is receiver-based; it does not piggyback any neighbor information. We prove theoretically that the proposed scheme achieves 100 percent deliverability. Simulation shows our scheme to be highly efficient. It consumes less energy, reduces the number of forwarding nodes almost to that of the benchmark, but maintains a high delivery ratio.

Keywords: Flooding scheme, receiver-based, full delivery, group forwarding, ad hoc networks.

1 Introduction

Flooding is a simple broadcast protocol for delivering a message to all nodes in a network. Many routing protocols for mobile ad hoc networks (MANETs), such as Ad-hoc On-Demand Distance Vector (AODV), Dynamic Source Routing (DSR), Zone Routing Protocol (ZRP), and Location-Aided Routing (LAR), use flooding as the basic mechanism to disseminate or to propagate route discovery control messages (Perkins, 2001; Abolhasan, 2004; Perkins, 2003; Rendong, 2006; Haas, 1997; Ko, 2000). An efficient flooding scheme is therefore useful to reduce the overhead of such routing protocols, decrease collisions, and improve network throughput. The simplest flooding technique, called pure flooding or blind flooding, is first discussed in Ho (1999). In this scheme, every node in the network retransmits a received broadcast message, when it receives this message for the first time. Despite its simplicity and guarantee that a flooding message can reach all nodes (if there are no collisions and the network is connected), pure flooding generates an excessive amount of redundant network traffic, because it requires every node to retransmit the message. Due to the broadcast nature of radio transmissions, when all nodes transmit a message in the network, there is a very high probability of signal collisions (Sinha, 2001). It may cause some nodes to fail to receive the flooding message. This is the so-called broadcast storm problem (Ni, 1999).

Existing efficient flooding schemes can be classified into three categories based on the information each node keeps: 1) no need of neighbour information, 2) keeping 1-hop neighbour information, or 3) keeping 2-hops neighbour information and more (Liu, H., 2007). We focus on the second category, where each node keeps 1-hop neighbour geographical location information. The authors in Liu, H. *et al.* (2007) distinguish algorithms in this category based on sender-based and receiver-based strategies, while the authors in Khabbazian & Bhargava (2008) term them as neighbour-designing and self-pruning algorithms, respectively. In a sender-based strategy, each node schedules a broadcast for a received flooding message if the node is selected by the sender and if it has not previously received this message. In a receiver-based strategy, a node schedules a broadcast for the first received copy of the flooding message. When the delay timer expires, the node may stop broadcasting the message if a responsibility condition is satisfied.

1.1 Related work

Pure flooding is inefficient. It leads to serious problems, including redundancy and collisions; so, it is not recommended for future applications (Tseng, 2001). Schemes in Cai *et al.* (2005), Wu & Li (1999), Pham & Choo (2008), Qayyum *et al.* (2002) and Lou & Wu (2004) have been proposed to reduce redundancy in flooding operations. However, these schemes either perform poorly in reducing redundant transmissions or require each node to maintain 2-hops neighbour information that incurs extra system overhead (Liu, H., 2007). Recently, there are several flooding schemes for the wireless environment that achieve very good results (Liu, H., 2007; Khabbazian, 2008; Le, 2008a; Le, 2008b; Liu, X., 2007). They are in the second category that uses 1-hop neighbour information to decide the forwarding nodes for a received flooding message.

A dominating set (DS) of a network is a subset of nodes such that every node in the network either is in the set or is a neighbour node of a node in the set (a CDS is a connected DS) (Wu, 1999; Stojmenovic, 2002; Dai, 2004). All forwarding nodes in a flooding operation form a CDS in the network, so the number of forwarding nodes that are required in the flooding operation is not less than the cardinality of minimal CDS (MCDS) in the network. Although computing MCDS is NP-hard, a ratio-8 approximation algorithm (R8A) exists (Wan, 2004). This scheme is used as a benchmark for comparison in Liu, H. *et al.* (2007), Khabbazian & Bhargava (2008), Le & Choo (2008a) and Liu, X. *et al.* (2007).

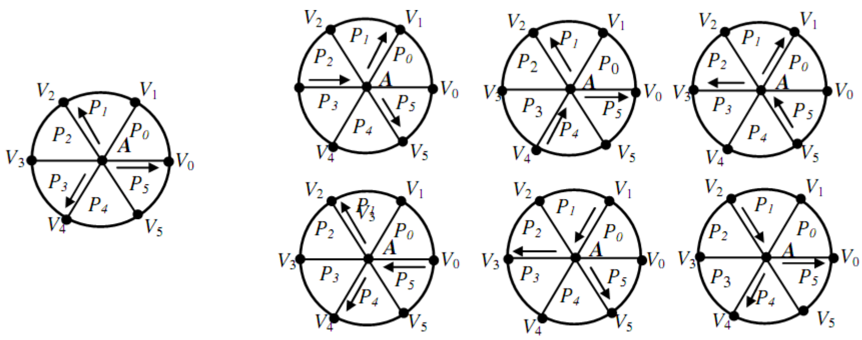
Liu, H. *et al.* (2007) propose a flooding scheme (we name it as 1HI) using the sender-based strategy. The mechanism of 1HI is summarized as follows: when a source node has a message to be flooded, based on the 1-hop neighbour geographical location information, it selects the next-hop retransmission nodes (together called the "forwarding set") and attaches this set to the message header. After receiving a flooding message for the first time, all receiver nodes verify whether they are in the sender's forwarding set. Every retransmission node computes its forwarding set in the same manner as the source node does. Then, based on the geographic location information, the receiver node optimizes its forwarding set by removing the nodes covered by the sender node and other lower-ID neighbouring retransmission nodes. After that, it relays the received message with the forwarding set attached. In this manner, the message eventually reaches all nodes in the network. The advantage of the sender-based 1HI flooding scheme is that it uses only 1-hop neighbour information; the protocol is easy to be implemented and has small overhead. However, this scheme has some disadvantages. First, the forwarding set is only locally optimized based on 1-hop neighbour information, and the number of forwarding nodes is relatively high. Second, the forwarding nodes are densely distributed along the network border. Most of the retransmissions broadcasted from network-border nodes are redundant, because their neighbours have already received this message from other previous-hop forwarding nodes.

The redundant transmissions of 1HI are the motivation for the work of Le & Choo (2008a) (called 2HBI). In this paper, the authors improve 1HI by using three rules proposed for deciding to remove a node from the forwarding set. Removing a node from the forwarding set reduces the number of nodes that retransmit a received flooding message. In evaluating performance, they show that their proposed improvement enhances 1HI. However, their scheme needs to collect 2-hops backward information to obtain better results. Collecting additional information could increase communication overhead and is inappropriate in mobile wireless environments where device nodes always move.

Another efficient sender-based flooding scheme is proposed in Liu, X. *et al.* (2007). The Vertex Forwarding scheme (VFS) guides the flooding procedure using a virtual hexagonal grid. Each node maps itself as a vertex of a hexagonal grid and keeps the knowledge of its adjacent vertex nodes, i.e., the neighbour nodes located at or nearest to adjacent vertices. Before a node broadcasts a message, it attaches the list of adjacent vertex nodes to the message. The nodes in the list are nominated as forwarding nodes. The main mechanism can be understood through the example in Figure 1. We consider the two cases where node *A* determines its forwarding nodes set *F*(*A*):

1) If *A* is a source node, three vertex nodes in the direction towards V_0, V_2, and V_4 are nominated as next hop forwarding nodes.
2) If *A* is a forwarding node, *A* selects two forwarding nodes from its forwarding candidates set.

The selection of forwarding nodes is based on direction information in the received flooding message. The efficiency of this scheme is very high; the number of forwarding nodes is close to the benchmark.



(a) Source node broadcasting (b) Forward node broadcasting

Figure 1. Forwarding nodes selection in Vertex Forwarding scheme.

In a receiver-based flooding strategy, the Localized Broadcasting algorithm (LBA) proposed by Khabbazian & Bhargava (2008) achieves very high efficiency. The authors show that their proposed localized broadcast algorithms can guarantee a reasonable bound on the number of forwarding nodes. The proposed self-pruning algorithm achieves 100 percent delivery, as well as guarantees a constant approximation ratio to the optimal solution. The algorithm to compute the proposed responsibility condition has near minimal computational complexity. LBA is based on the following responsibility condition: node N_A is pruned (has non-forwarding status) if it is not responsible for any of its neighbours. Node N_A is not responsible for its neighbour N_B if N_B has received the message or if there is another node N_C such that N_C has received the message and N_B is closer to N_C than N_A. Figure 2 shows an example of the algorithm. Node N_A has six neighbours. Suppose that N_A has received a flooding message from N_H. Recall that N_A extracts the list of N_H's neighbours from the received message. Therefore, it knows that N_E, N_F and N_G have received the message and N_B, N_C, and N_D have not. Based on the responsibility condition, N_A is not required to retransmit the message because: $d(N_B, N_E)$

$< d(N_B, N_E)$, $d(N_C, N_F) < d(N_C, N_A)$ and $d(N_D, N_G) < d(N_D, N_A)$ (or $d(N_D, N_F) < d(N_D, N_A)$), where $d(N_A, N_B)$ is the Euclidian distance between two nodes N_A and N_B.

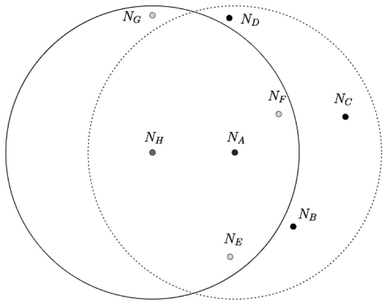


Figure 2. Self-pruning example based on responsibility condition.

1.2 Motivation

1HI is an efficient flooding scheme that achieves local optimality in two senses: the number of forwarding nodes and the time complexity for computing forwarding nodes. The authors also prove that their scheme has 100 percent deliverability for flooding. The performance of this scheme outperforms their previous work (Cai, 2005; Wu, 1999), but there are still many redundancies. The gap between the benchmark and 1HI is quite large. 2HBI, an improvement of 1HI, can achieve better results; however, the gap between the scheme and the benchmark is still large. Besides, 2HBI makes use of the information of 2-hops backward neighbours to improve 1HI. This is the trade-off as 2-hops information is unsuitable in mobile environments. With VFS, the performance of the proposed scheme is very high. The number of forwarding nodes is close to the benchmark. However, this scheme cannot guarantee 100 percent deliverability. The example in Figure 3 shows a situation in which a message cannot be flooded to the entire network. Suppose that node A has four neighbours: N_1, N_2, N_3, and N_4. Nodes N_1, N_2, and N_3 are chosen by node A as the forwarding nodes, and they should retransmit a flooding message received from A. However, node N_5 can communicate with node N_4 only, but node N_4 does not retransmit the received message due to not being in the forwarding set of node A. Therefore, in this case node N_5 cannot receive the flooding message. That means this message cannot be delivered to the entire network.

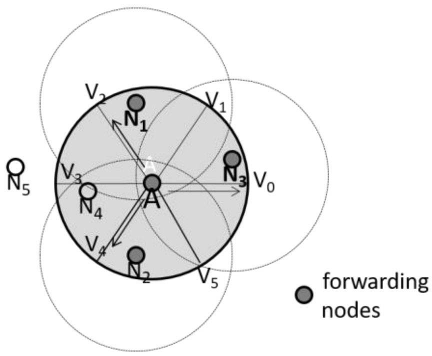


Figure 3. Missed delivery example in Vertex Forwarding scheme

LBA has impressive performance among the receiver-based flooding schemes. The authors show that their scheme outperforms 1HI. The number of forwarding nodes is slightly smaller than the benchmark (Wan, 2004). However, in the algorithm each forwarding node adds a list of its 1-hop neighbours' IDs and positions to a broadcast message. This information is extracted and used to determine the next-hop node status (forwarding/non-forwarding). Even though the authors prove that the list of 1-hop neighbours can be replaced by a smaller set of representative neighbours, the piggyback information increases message size. Large message size consumes more energy in transmission and increases communication collisions. A high collision environment could consume more retransmission energy and affect the deliverability of the scheme also.

1.3 Our contribution

Motivated by the drawbacks of previous work, we propose a receiver-based flooding scheme for mobile ad hoc networks. Our proposed flooding scheme requires each node to keep only 1-hop neighbourhood information, including the node IDs and their geographic locations. The location information of each node can be obtained via GPS (Getting, 1993) or some distributed localization methods (Langendone, 2003) when GPS service is not available. We prove that our flooding scheme guarantees 100 percent deliverability for an ideal Media Access Control (MAC) layer, where no collision takes place.

Moreover, we consider our proposed scheme's mobility handling applied to mobile environments. We also relax several system model assumptions, or replace them with practical ones, to improve the practicality of the proposed flooding scheme. Finally, we verify the performance and analytical results by computer simulation along with previous work. The simulation results show that the proposed flooding scheme outperforms previous work in many aspects.

The remainder of the paper is organized as follows. We propose an efficient flooding scheme for wireless ad hoc networks in Section 2. In Section 3, we discuss the simulation results of our flooding scheme, using the *ns*-2 simulator, and compare its performance to the best-known flooding algorithms. Finally, we conclude our work in Section 4.

2 The Proposed Flooding Scheme

We describe the assumptions of the proposed algorithm as follows: consider a wireless network as a collection of N nodes placed randomly in a plane; each node is equipped with an omni-directional antenna that has radio transmission range R. We call two distinct nodes neighbours if they are in transmission range of each other (that is, the Euclidean distance between them is less than or equal to R). We assume that each node is aware of its geographical location. Each node periodically broadcasts a short HELLO message containing its unique ID and its location to obtain the 1-hop location information of neighbour nodes.

2.1 Group forwarding scheme using 1-hop neighbours location information

The proposed flooding scheme follows a receiver-based strategy, so the general procedure for the algorithm is presented as Algorithm 1 (Khabbazian, 2008): when first receiving a copy of a flooding message, a node schedules a broadcast for a period. When the delay timer expires, the node considers whether it should retransmit the message if a specified responsibility condition is satisfied. During the delay timer, the node listens to the broadcast messages of neighbours to collect information needed for the responsibility condition.

Algorithm 1. General structure of self-pruning algorithms.

1. **If** the message *M* has been received before
2.   Drop the message;
3. **Else**
4.   Set a delay timer;
5. **When** the delay timer expires:
6.   Decide whether or not to broadcast *M* based on the responsibility condition.

Algorithm 1 is a general procedure for a receiver-based flooding algorithm. The responsibility condition in our proposed flooding scheme originates from the following observation: if the identical area is covered by multiple nodes that receive the same message from the same sender s, the one farthest from s is the node that should retransmit the message. In Figure 4, we assume that node s broadcasts a message, nodes r, a, b, and c receive the message since they are in the transmission range of s. Only node c should retransmit the message because c can cover further areas compare to the retransmissions of nodes a, b, or r. By covering a larger area, we may reduce the number of forwarding nodes that need to broadcast messages to cover the entire network.

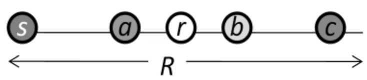


Figure 4. A scenario for node deployment

Using the above observation, we propose a novel flooding algorithm based on one round of neighbourhood information exchange. The proposed algorithm, Algorithm 2, is a simple modification of Algorithm 1.

Algorithm 2. The proposed flooding algorithm.

1. **If** the message *M* has been received before

2.	Drop the message;
3.	**Else**
	Decide whether to broadcast M or not based on the retransmission condition
4.	**If** the retransmission condition is satisfied
5.	**Set** a delay timer;
6.	**When** the delay timer expires: broadcast message M.

The difference between Algorithm 1 and Algorithm 2 is the order of the delay timer (line 4 in Algorithm 1 and line 5 in Algorithm 2, respectively). In Algorithm 1, we set the timer after the first time receiving a flooding message; then, the node collects the information in the overheard broadcast message of neighbours until the timer expires. The collected information is used to check the responsibility condition. However, in Algorithm 2, we set the timer only if the retransmission condition is satisfied. That means that only the nodes that need to retransmit the message set their timer. When the timer expires, nodes broadcast the received flooding message. This change reduces storage overhead in each node. In Algorithm 1, every node sets the timer and then collects the information and stores it in memory. However, in Algorithm 2, after receiving a flooding message, the node checks the responsibility condition immediately. Only some forwarding nodes should set the delay timer. Therefore, we can reduce storage and processing overhead that result in energy consumption. In the following section, we detail our proposed flooding algorithm.

A) Group division

To describe our proposed flooding scheme, we introduce the following definitions:

Definition 1. *The coverage disk of node u, $c(u)$,* is a disk that is centred at u and whose radius is the transmission range of node u.

Since all neighbours of node u should be covered by $c(u)$, we say “u covers v” or “v is covered by u” when v is a neighbour node of u.

Definition 2. *The coverage area of a set of nodes A, $C(A)$,* is the union of coverage disks of nodes in A.

We simply state “the area is covered by A” if the area is within $C(A)$.

Definition 3. The distance between two nodes, u and v, called $d(u, v)$, is the Euclidian distance of those two nodes in the Cartesian plane: $d(u,v) = \sqrt{(u_x - v_x)^2 + (u_y - v_y)^2}$.

Suppose r is a node that receives a flooding message for the first time and s is the message sender (see Figure 5). Node r divides its neighbour nodes into three groups using 1-hop neighbour location information as follows:

- *Group 1*: Nodes that are in transmission range of s, and the distance from them to s is shorter than the distance from r to s: $\{u|u \in c(r) \text{ and } u \in c(s) \text{ and } d(s,u) \leq d(s,r)\}$.
- *Group 2*: Nodes that are in transmission range of s, and the distance from them to s is longer than the distance from r to s: $\{u|u \in c(r) \text{ and } u \in c(s) \text{ and } d(s,u) > d(s,r)\}$.
- *Group 3*: Nodes that are not within transmission range of s: $\{u|u \in c(r) \text{ and } u \notin c(s)\}$.

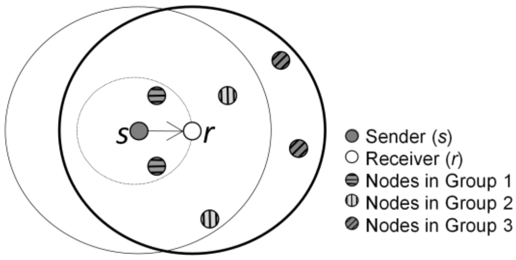


Figure 5. An example of dividing neighbours into 3 groups

Let $List_r^{Group\ i}$ be the set of nodes in *Group i* of node r. Algorithm 3 below is used to divide neighbour nodes of one node into 3 groups.

Algorithm 3. Dividing neighbour nodes into 3 groups.

1.	**Foreach** node u in $c(r)$
2.	**If** $d(s, u) > R$ then **Add** u to $List_r^{Group3}$
3.	**Else If** $d(s, u) > d(s, r)$ then **Add** u *to* $List_r^{Group2}$
4.	**Else If** $d(s, u) \leq d(s, r)$ then **Add** u to $List_r^{Group1}$
5.	Endfor

B) Relaying message

After dividing neighbour nodes into groups, node r checks the following condition to decide whether it should forward a received flooding message, or not.

Retransmission condition. Node r should retransmit a received flooding message if and only if there is a neighbour node v that has not received the message ($v \in List_r^{Group3}$) and v cannot be covered by any node in *Group 2* of r ($v \notin C\left(List_r^{Group2}\right)$).

In other words, node r should not retransmit a received flooding message if *Group 3* is empty or if all nodes in *Group 3* are covered by nodes in *Group 2*.

Nodes in *Group 3* are inside the coverage area of node r; it is clear that, if all nodes in *Group 3* are covered by nodes in *Group 2*, then the broadcasts by r and nodes in *Group 2* will cause nodes in *Group 3* to receive the same flooding message more than one time. We can eliminate this redundancy by letting either r or the nodes in *Group 2* retransmit the message (but not both). In our proposed scheme, we choose nodes in *Group 2* to be responsible for retransmitting the message, because the nodes in *Group 2* cover an area at least as large as the coverage area of node *r*. So, if nodes in *Group 2* broadcast the message, then more nodes can receive the flooding message. Besides, nodes in *Group 2* are also further from the sender *s* than from node *r* to *s*, so they can cover a larger area compared to choosing *r* as the forwarding node.

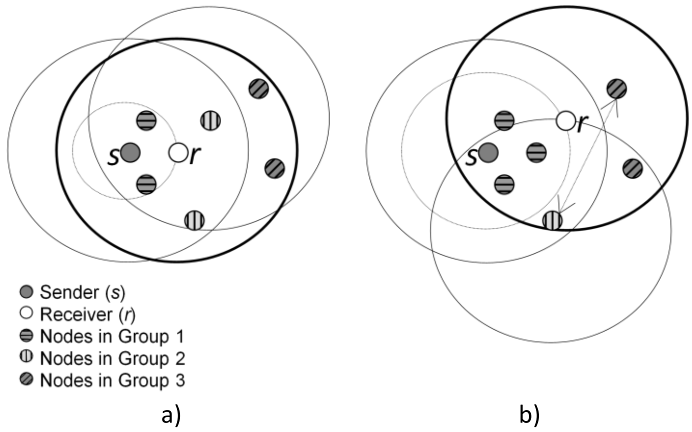


Figure 6. Examples of checking the retransmission condition

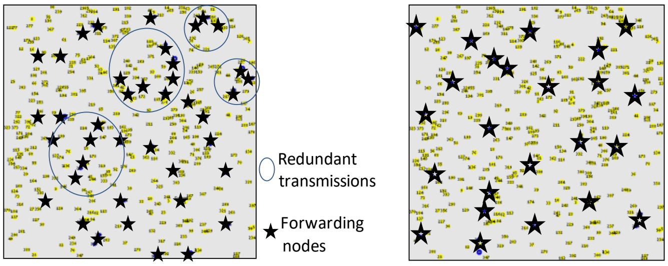
We give an algorithm to determine the coverage of nodes in *Group 3* by the nodes in *Group 2*. The following pseudocode (Algorithm 4) is used to determine the condition whether a node should forward a received flooding message. If node *r* receives a message from sender *s* as shown in Figure 5, it divides its neighbour nodes into 3 groups and then checks whether the retransmission condition is satisfied. Finally, if the retransmission condition is satisfied (return *true*), then *r* should retransmit the received message to its neighbours.

Algorithm 4. Computing the retransmission condition.

Foreach node u in $List_r^{Group3}$
    covered = *false*
    Foreach node v in $List_r^{Group2}$
        If $u \in c(v)$ then // $u \in c(v)$
            covered = *true*
            Break
        Endif
    Endfor
    If *covered* = *false* then **Return** *true*
Endfor
Return *false*

To illustrate the proposed flooding scheme, we consider the example in Figure 6. Suppose that *s* broadcasts a message and *r* receives the message from *s*. Node *r* divides its neighbours into three groups. Nodes in *Group 3* of *r* are outside the transmission range of *s* so they cannot receive the message from s. In the situation of Figure 6(a), r knows that all nodes in *Group 3* are covered by nodes in *Group 2*. Based on the retransmission condition, r is not required to retransmit the flooding message. For the case in Figure 6(b), there is one node in *Group 3* that cannot be covered by any nodes in *Group 2*, so node r should retransmit the message to cover that node.

2.2 Efficiency improvement



a) b)

Figure 7. Broadcast nodes in a 1000x1000m^2 area with 400 nodes

Figure 7(a) illustrates an instance of using the proposed flooding algorithm to flood a message to an entire network where 400 nodes are randomly placed in a square area of 1000x1000m^2, and the node radio transmission range is set to 250m. From the figure, we observe that there are several broadcast nodes close to each other. Broadcast nodes stay close together; that is, the coverage areas overlap. The nodes inside this area receive the flooding message many times (duplicated messages) and then collisions are relatively high. Based on this observation, we propose Algorithms 5 and 7 to improve Algorithms 4 and 2, respectively.

Algorithm 5. Modification of computing retransmission condition.

Set $List_r^{NotRec}$ as an empty list;

Foreach node u in $List_r^{Group3}$

  covered = *false*

  Foreach node v in $List_r^{Group2}$

    If $d(v,u) \leq R$ then // $u \in c(v)$

      covered = *true*;

  Endfor

  If *covered* = *false* then **Add** u to $List_r^{NotRec}$

  // due to $u \notin C\left(List_r^{Group2}\right)$

Endfor

If $List_r^{NotRec}$ is not empty then **Return** *true*

Return *false*

In Algorithm 5, node r computes a list of nodes in *Group 3* that cannot be covered by nodes in *Group 2* ($List_r^{NotRec}$). If this list is empty, then node r should not retransmit the received flooding message. When the retransmission condition is satisfied ($List_r^{NotRec}$ is not empty), then node r sets a delay timer (Algorithm 7, line 8). During this period, node r listens to the forwarding messages of its neighbours and stores them (the node IDs and locations of neighbour nodes that broadcast the messages) into $List_r^{NeiBrd}$ (Algorithm 7, lines 3, 4, 9). Node r can stop its scheduled retransmission if and only if all nodes in $List_r^{NotRec}$ can be covered by nodes in $List_r^{NeiBrd}$ ($List_r^{NotRec} \in C\left(List_r^{NeiBrd}\right)$): we call this the second retransmission condition (Algorithm 6). That is, node r can stop its scheduled retransmission because all nodes in $List_r^{NotRec}$, which had not received the flooding message before r set its delay timer, have already received this message from other nodes during the timer period. Therefore, the retransmission of r should be redundant and unnecessary. With the modification in Algorithm 7, node r has a chance to stop forwarding a received flooding message if the second retransmission condition is not satisfied. That means we can further reduce the number of forwarding nodes in the proposed flooding algorithm.

Algorithm 6. Computing the second retransmission condition.

Foreach node u in $List_r^{NotRec}$
    covered = *false*
    Foreach node v in $List_r^{NeiBrd}$
        If $d(v, u) \leq R$ then *covered* = *true*; // $u \in c(v)$
    Endfor
    If *covered* = *false* then **Return** *true*
Return *false*

Algorithm 7. Improvement of the proposed flooding algorithm.

1. **If** the message *M* has been received before
2.   **If** the node is in listening mode
3.   Extract the sender ID from the packet;
4.   Add the sender location to the list $List_r^{NeiBrd}$
5.   Drop the message
6. **Else**
7.   **If** the retransmission condition is satisfied // Algorithm 5
8.   Set a delay timer;
9.   Set to listening mode;
10. **When** the delay timer expires
11.   **If** the second retransmission condition is satisfied // Algorithm 6
12.   Broadcast message *M*

From this point to the end of this paper, we consider Algorithm 7 and its dependency algorithms (Algorithms 3, 5, and 6) as our proposed scheme.

In the proposed flooding scheme, when a node divides its neighbours into 3 groups (based on a flooding message received from a sender) or a node checks the coverage of two other nodes, we refer to the Euclidian distance. Two square operators and one square-root operator are required to calculate the distance between two nodes. Those operators are complex, consuming time and CPU instructions. In a mobile wireless environment, a device's ability is limited, so computing the Euclidian distance many times consumes node energy. We make use of data structures to reduce computation overhead. We use a hash table H to store the pre-computed Euclidian distance between two neighbour nodes. On the first use of a distance value (i.e., the distance between nodes r and u), we calculate and store the value into the table ($H(u)$ = value). Then, any later usage of the Euclidian distance between node r and its neighbour u can be retrieved by the function $H(u)$.

2.3 100 percent deliverability

In this section, we prove that our proposed retransmission condition guarantees 100 percent deliverability. To prove this property, we assume that nodes are static, the network is connected, and the MAC layer is ideal, i.e., there is no transmission error.

Theorem. The retransmission conditions (Algorithms 5 and 6) guarantee that all network nodes receive the flooding message.

In Algorithm 5, we check whether all nodes in $List_r^{Group3}$ are covered by nodes in $List_r^{Group2}$. If yes, node r should not retransmit a received flooding message. Suppose that node r receives a message from node s. After checking the retransmission condition, if node r stops forwarding the received message, then we prove that all neighbour nodes of r that have not received this flooding message can receive a forwarding message from another neighbour of nodes s and r. Let us assume that v is a neighbour node of r that has not received the message. Due to the stopping of the forwarding message from r, we can find one neighbour node $u_1 \in List_r^{NotRec}$, such that u_1 has received the message from s and u_1 can cover v: $u_1 \in c(s)$, $v \in c(u_1)$, and $d(s, u_1) > d(s, r)$.

If u_1 retransmits the message received from s, then v is covered (due to $v \in c(u_1)$). If u_1 stops forwarding, since it does not satisfy the retransmission condition, then there is one neighbour node $u_2 \in List_{u_1}^{Group2}$, such that u_2 has received the message from s and u_2 covers v: $u_2 \in c(s)$, $v \in c(u_2)$, and $d(s, u_2) > d(s, u_1) > d(s, r)$.

If u_2 stops forwarding, there must be a node named u_3 that should take care of the retransmission. The recurrence gives us a sequence of nodes taking care of forwarding the message such that: $u_1 \in List_{u_{i-1}}^{Group2}$ with $u_i \in c(s)$, $v \in c(u_i)$, and $d(s, u_i) > d(s, u_{i-1}) > \ldots > d(s, r)$.

The number of nodes is finite, so the number of neighbour nodes of s is finite. The transmission range of s is also finite, so $d(s, u_i)$ is limited by a constant value. Therefore, there must be a node u_j such that u_j has received the message from s and $\neg\exists u_k$: $u_k \in c(s) \wedge v \in c(u_k) \wedge d(s, u_k) > d(s, u_j) > \ldots > d(s, r)$. Thus, u_j satisfies the retransmission condition. That is, u_j has to forward the flooding message received from s. Then, node v can receive the message originating from node s.

In Algorithm 6, the second retransmission condition, node r stops forwarding a received message if all nodes stored in $List_r^{NotRec}$ have already received a flooding message from other forwarding nodes. This condition does not affect the deliverability because r and all its neighbours have received the flooding message; then retransmission of r is redundant and can be omitted. Therefore, the theorem is proved.

2.4 Relaxing some of the system assumptions

The proposed algorithm's 100 percent deliverability is based on the assumptions made in Section 2.3. However, some of these assumptions are impractical. For example, the node location information may not be 100 percent accurate in real applications. Our proposed algorithm can be slightly modified to deal with imperfect location information. Suppose location information error is ε. For example, in Figure 8(a), the position of node u is u's self-estimated location and u's actual location is within a circle with radius of 2ε. We can simply make the valid coverage area of each node disk radius $(R - 2\varepsilon)$ to compensate for this location error. In doing so, we can say that, if the distance between node r and node s is less than $(R - 2\varepsilon)$, then node r can receive a message sent by s, because we have

$$\Gamma(r, s) - 2\varepsilon \leq d(r, s) \leq \Gamma(r, s) + 2\varepsilon, \tag{1}$$

where $\Gamma(r, s)$ is the exact distance between the nodes r and s ($d(r, s)$ is calculated based on the inaccurate location information of the two nodes). If $d(r, s) \leq (R - 2\varepsilon)$, then

$$\begin{aligned} &\Gamma(r, s) - 2\varepsilon \leq d(r, s) \leq \Gamma(r, s) + 2\varepsilon \\ \Leftrightarrow\ &\Gamma(r, s) \leq R \end{aligned} \tag{2}$$

That is, node r is in transmission range of node s. We modify Algorithm 3, 5 and 6 to group neighbour nodes and compute the retransmission condition under inaccurate position information by changing the function of checking the coverage of two nodes u and v (Algorithm 3 lines 2, 3, 4; Algorithm 5 line 5; and Algorithm 6 line 3, respectively) to:

$$v \in c(u) \text{ iff } d(u,v) \leq R - 2\varepsilon \tag{3}$$

Two more assumptions that can be relaxed are the homogeneous network assumption and that the coverage disk of one node is a circle. In practice, devices may have different radio transmission ranges and the coverage disk is only close to a circular shape (see Figure 8(b)). Let us use R_u^L to denote a lower bound of node u's radio transmission range. Suppose that each node includes the lower bound of its transmission range into the HELLO message. Based on that information, the receiver node r can compute exactly the retransmission condition by changing the coverage checking function in Algorithm 3, 5, and 6 as follows:

$$v \in c(u) \text{ iff } d(u,v) \leq R_u^L - 2\varepsilon \tag{4}$$

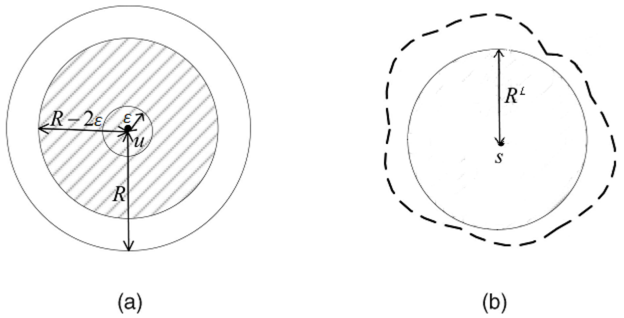


Figure 8. Reducing coverage disk to compensate for the error in location and radius

Moreover, nodes may be mobile in ad hoc network environments, causing network topology to change. For the flooding scheme, each node maintains its neighbour information and sets the expiration status to the Euclidian distance in the Hash Table H. Using this method, we can handle mobility and our proposed flooding scheme can be applied to mobile environments.

3- Results and Discussion

To analyse the performance of our proposed flooding scheme, we compare it to three delivery-guaranteed flooding schemes: 1HI (Liu, H., 2007), 2HBI (Le, 2008a) and LBA (Khabbazian, 2008). We also compare it to the VFS scheme (Liu, X., 2007) that does not guarantee 100 percent deliverability. Table 1 shows the information of the target schemes for comparison.

Table 1. Five flooding schemes in simulation experiments

Algorithms	Piggybacking	Strategies
1HI	Yes	Sender-based
2HBI	Yes	Sender-based
VFS	Yes	Sender-based
LBA	Yes	Receiver-based
Proposed Scheme	No	Receiver-based

We run simulations under the *ns*-2 tools with the CMU wireless extension (CMU, no date). The simulation parameters are listed in Table 2.

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Table 2. Applications in each class

Parameter	Value
Simulator	*ns*-2
MAC Layer	IEEE 802.11
Data Packet Size	256 bytes
Bandwidth	2Mb/s
Number of Nodes	50~1000 nodes
Radio Range	250m
Size of Square Area	1000x1000m^2
Number of Trails	1000 times

The two-ray ground reflection model is adopted as the radio propagation model. The MAC layer scheme follows the IEEE 802.11 MAC specification. We use the broadcast mode with no RTS/CTS/ACK mechanisms for all message transmissions. The bandwidth of a wireless channel is set to 2Mb/s as the default. Notice that all of the schemes require the node to send a HELLO message to its 1-hop neighbours periodically, so this cost is ignored in our performance study. We analyse flooding efficiency in terms of the following metrics:

- The forwarding ratio is the ratio of forwarding nodes in the flooding operation to the total number of nodes in the network. The main objective of efficient flooding schemes is to reduce the number of forwarding nodes so that redundant transmission is minimized. Thus, this metric is an important criterion.
- Reducing the number of forwarding nodes in flooding would effectively reduce the number of signal collisions in the network. We also use the number of collisions to evaluate the efficiency of the flooding schemes. The number of collisions is defined to be the sum of the collisions experienced by each node before it receives a flooding message correctly.
- The delivery ratio is the ratio of the nodes that received packets to the number of nodes in the network for one flooding operation. Signal collisions eventually affect the delivery of flooding messages. Some nodes in the network miss the flooding messages, due to the large number of collisions. This metric is also important to further study algorithmic efficiency.

In each simulation run, we generate a specified number of nodes and randomly place them within a square area (using uniform distribution). The source that initiates a flooding message is randomly picked from network nodes. Only one flooding occurs at any one time (except in the experiments on delivery ratio). Four flooding schemes and the benchmark (Wan, 2004) are simulated and compared with our proposed scheme under the same conditions. The results presented in the following figures are the means from 100 separate runs. In the simulation of the performance on the forwarding ratio of the flooding schemes over different network densities, we fix the network size and vary the number of nodes. A specified number of nodes, from 50 to 1000, are randomly placed on a 1000x1000m^2 area. The transmission range is set to 250m.

Figure 7(b) illustrates an instance using the proposed flooding scheme, where R=250m, N=400 nodes, and the nodes are placed in a square area of 1000x1000m^2. Twenty-four nodes retransmit a flooding message to an entire network.

Figure 9(a) shows the ratio of forwarding nodes over the total number of nodes in the network. The performance of our flooding scheme is significantly better than that of 1HI and 2HBI for the number of forwarding nodes. We achieve similar performance compared to LBA and VFS.

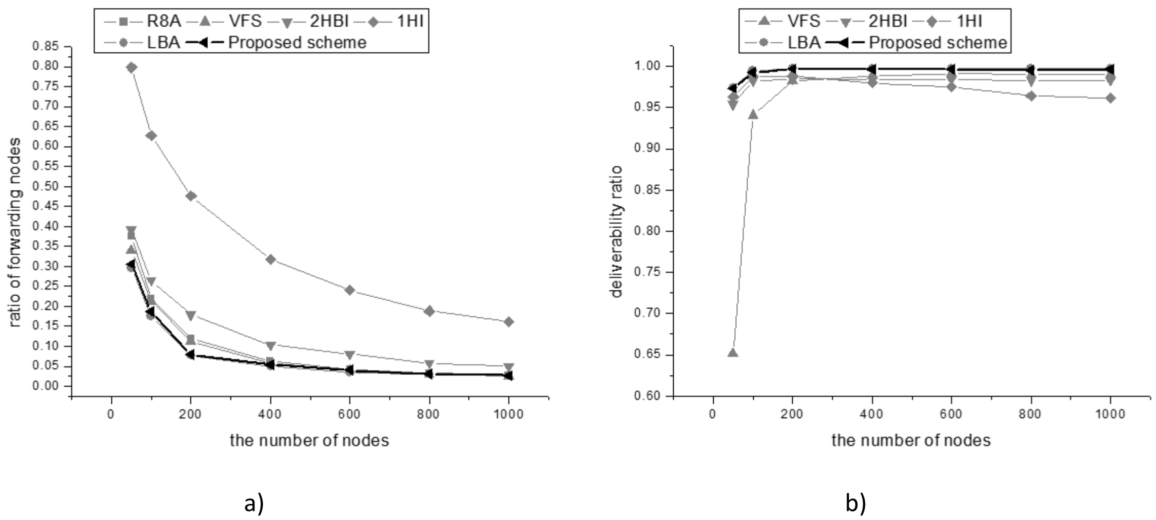
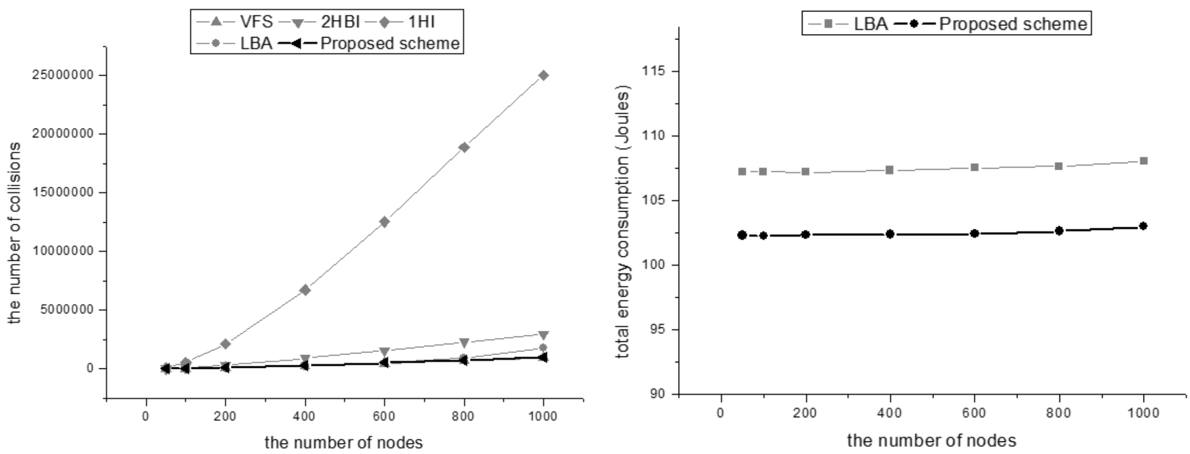


Figure 9. Ratio of forwarding nodes and delivery ratio against number of nodes

In the delivery ratio experiments, network load is set to 10 packets/s; that is, the network generates 10 flooding messages per second on average. The delivery ratio is calculated over 100 seconds. Since 1HI, 2HBI, LBA and our proposed scheme guarantee full deliverability, the results show that these schemes achieve nearly 100 percent delivery ratio. In the high network load and node density cases, collisions cause missing packets, so the schemes cannot obtain 100 percent delivery, as shown Figure 9(b). For VFS, due to not guaranteeing delivery, the performance over a sparse network is very low (e.g., networks of 50 to 200 nodes in the area of 10^6m^2).

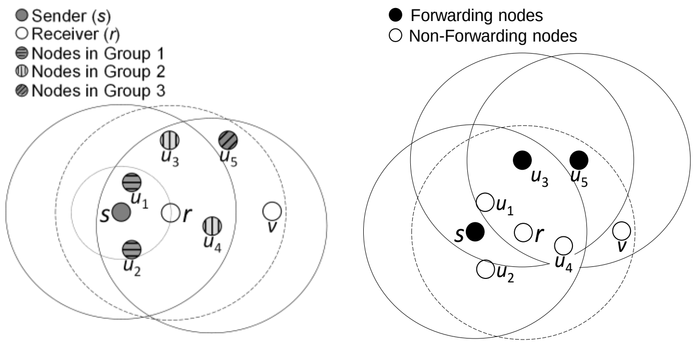
Figure 10(a) shows the experimental results on the number of collisions in the network. Due to the small number of forwarding nodes, LBA, VFS and our proposed scheme outperform 1HI and 2HBI. In a dense network, our scheme has fewer collisions compared to LBA, due to the varied sizes of the flooding messages. Our scheme requires smaller message size than LBA, so the number of collisions in dense networks is also smaller.



a) b)

Figure 10. Ratio of forwarding nodes against number of nodes

Our proposed scheme outperforms 1HI and 2HBI (Figures 9 and 10(a)) in the case of 100 percent delivery-guaranteed flooding schemes. At the same time, our scheme achieves similar performance compared to LBA, since the two schemes are receiver-based and the method is somewhat similar. However, the approaches of the two flooding schemes differ. LBA selects the node nearest the non-covered node to retransmit the flooding message. In contrast, our proposed scheme is based on choosing the node that is furthest from the sender to be the forwarding node. Our approach is based on the observation that we want to cover an area farthest from the sender. We illustrate the difference between LBA and our proposed scheme in Figure 11. Assume that node *s* first broadcasts a message to its neighbours. Node *r* receives the message and decides not to retransmit because the responsibility/retransmission condition is not satisfied. In Figure 11(a), according to our proposed retransmission condition, node u_4 which is furthest away from sender *s* should take care of forwarding the received flooding message. In contrast, Figure 11(b) shows the situation of using the responsibility condition in the LBA scheme to decide forwarding node. Node u_3 should forward the flooding message because it is nearest to u_5, which is a node not covered by sender *s*.

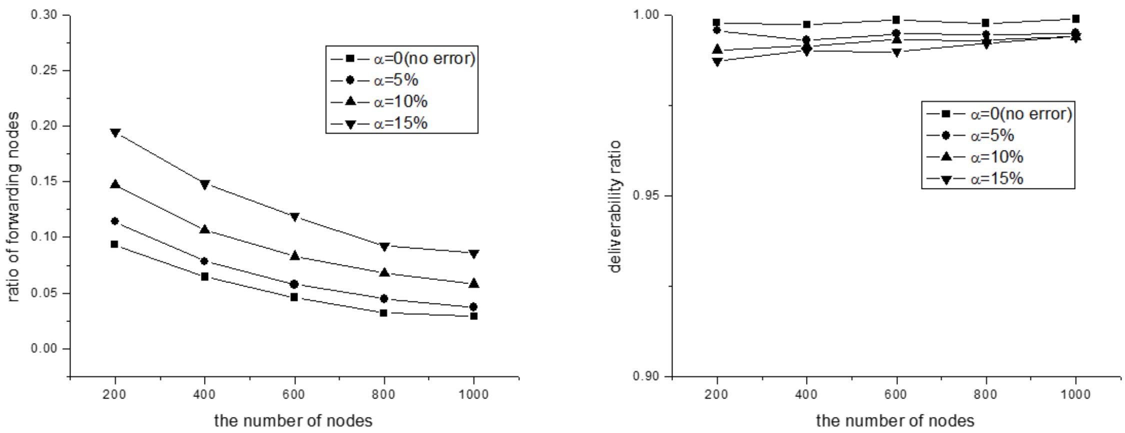


a) b)

Figure 11. Example of forwarding node selections in LBA (b) and our scheme (a)

The example above shows that different approaches bring different results (set of forwarding nodes) between LBA and our proposed scheme. Although LBA and our proposed flooding scheme have similar performance in terms of the number of forwarding nodes and delivery ratio, LBA requires piggybacking information in the broadcast message. This causes the message size to be larger. Transmission energy consumption depends on message length. Figure 10(b) shows the energy consumption of two flooding schemes. From the figure, we can see that energy consumption seems to be independent of the number of nodes. That is because the number of forwarding nodes does not change much when we vary the number of nodes in a constant network area. On the whole, our proposed scheme consumes less energy; and so our scheme can prolong network lifetime more than LBA.

We also evaluate the performance of our proposed algorithm when there is inaccuracy in position information. We set the radio transmission range to R=250*m* and fixed the maximum position error to αR, where $0 \le \alpha \le 0.15$. Figure 12(a) shows the ratio of forwarding nodes for a given α. We see that the performance of the proposed flooding scheme just slightly degrades as the position error increases. Finally, we inspect the deliverability of the proposed scheme on the condition of uncertain position information (the network load is set to 10 pkt/s). As shown in Figure 12(b), the simulation results validate that, in spite of the existing uncertainty of position information, the proposed scheme achieves almost 100% deliverability.



a) b)

Figure 12. Ratio of forwarding nodes and delivery ratio with uncertain position information

4- Conclusions

Traditional approaches to the implementation of flooding protocols suffer from excessive message redundancy, resource contention, and signal collision. In this paper, we address the efficient flooding problem in a wireless ad hoc network. The paper presents an efficient flooding scheme that uses only 1-hop neighbour location information and follows a receiver-based strategy. We show that the proposed flooding scheme can guarantee 100 percent deliverability. Simulation results validate that our proposed scheme uses fewer forwarding nodes, incurs fewer collisions, obtains a higher delivery ratio, and is more highly scalable than 1HI and 2HBI. The ratio of forwarding nodes of our proposed scheme is similar to VFS and LBA; however, our scheme is better than VFS in terms of delivery ratio and is better than LBA in terms of energy consumption – an important issue to prolong the network lifetime.

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