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Development of wireless network planning software for rural community use

A thesis

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of

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by

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Abstract

Rural New Zealand has poor access to broadband Internet. The CRCnet project at the University of Waikato identified point-to-point wireless technology as an appropriate solution, and built networks for rural communities. The project identified viable solutions using low-cost wireless technologies and commodity hardware, allowing them to establish general construction guidelines for planning rural wireless networks. The CRCnet researchers speculated that these general construction guidelines had simplified the wireless network problem to a point at which it seemed feasible to embed the guidelines within a software tool. A significant observation by the CRCnet researchers was that community members are collectively aware of much of the local information that is required in the planning process. Bringing these two ideas together, this thesis hypothesises that a software tool could be designed to enable members of rural communities to plan their own wireless networks.

To investigate this hypothesis, a wireless network planning system (WiPlan) was developed. WiPlan includes a tutorial that takes the unique approach of teaching the user process rather than the detail of network planning. WiPlan was evaluated using a novel evaluation technique structured as a role-playing game. The study design provided participants with local knowledge appropriate for their planning roles. In two trials, WiPlan was found to support participants in successfully planning feasible networks, soliciting local knowledge as needed throughout the planning process. Participants in both trials were able to use the techniques introduced by the tutorial while planning their wireless network and successfully plan feasible wireless networks within budget in both study trials. This thesis explores the feasibility of designing a wireless networking planning tool, that can assist members of rural communities with no expertise in wireless network planning, to plan a feasible network and provides reasonable evidence to support the claim that such a planning tool is feasible.

Declaration

The work in this thesis is based on research carried in the Department of Computing and Mathematical Sciences at the University of Waikato, New Zealand. No part of this thesis has been submitted elsewhere for any other degree or qualification and it all my own work unless referenced to the contrary in the text.

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Chapter 1

Introduction

The impact of the Internet on human lives is increasing every day. More and more services are becoming available online that help to enhance the standard of living for many people. Social networking has become viral with Facebook [5] and Twitter [23] the dominant two. Facebook, which launched in 2004, had more than 500 million active users in 2010. Twitter launched in 2006 and is estimated to have 190 million users in 2010.

Economic opportunities have also increased with real-world stores opening online stores and the introduction of online-only stores. Online auction sites such as EBay [3] and Trademe [22] are also providing economic opportunities. People want to be able to experience these services and opportunities online but unfortunately there are still areas in the world that have poor Internet connectivity, particularly rural areas. This thesis has a particular focus on rural New Zealand but the findings in this thesis apply to any of these areas where the population density is sparse. The definition of sparse in this thesis refers to population densities of 2.6 to 0.5 people per square kilometre [32].

Broadband refers to the broad number or band of frequencies used to transfer a signal at significant speed. The broader the band of frequencies, the more the speed increases. More commonly though, broadband has become the term for describing a high-speed connection to the Internet. The OECD have defined broadband as having download data transfer rates equal to or faster than 256 kbps [63]. The OECD definition of broadband is used in this thesis. In New Zealand, as of 2009, 78% of rural households have access to the Internet - 55% via broadband access and 23% via dialup [39]. Approximately 54% of rural households on dialup do not have broadband because it is not available in their area. Also, 30% of rural households on dialup do not have broadband because they believe that broadband is too expensive. According to Net Index, New Zealand's average broadband speed is 7.64 Mbps [11].

New Zealand has a long history of low telecommunications investment in rural areas [42]. DSL, the most common technology for delivering broadband Internet, is ineffective at distances beyond seven kilometres from a DSL exchange [42] and installing new DSL exchanges can cost hundreds of thousands of dollars. Telecommunication companies conventionally do not profit much from providing Internet access and spending a large amount of money up-front on rural areas would receive a poor return. Investing in telecommunication ventures requires not only the cost of the network infrastructure, but also the cost of network planning experts. Suitable experts may have limited availability and rural networks require extensive time for the expert to become acquainted with the rural area.

The advantage that wireless technology has over wired technology is that the planning effort is concentrated on connection points, rather than the route of the physical communication medium. For large rural areas with sparse populations of people, this is an attractive advantage. Terrain and other factors have less of an influence on wireless technologies than wired technologies because wired technology needs to be physically trenched in the ground or using aerial deployment, where the cables are carried overhead by large poles. Rural roll-out of wired technology costs up to $4000 per kilometre for trenching and up to $5000 per kilometre for aerial deployment [98].

1.1 Wireless technology solutions

This section introduces five wireless network technologies and describes the advantages and disadvantages of each for rural areas. The five technologies are wireless sensor networks, satellite networks, cellular networks, wireless mesh networks and wireless point-to-point networks. Requirements for a wireless technology appropriate for rural communities include:

- Bandwidth of at least 1 Mbps
- Low-latency, particularly for interactive applications such as Skype and online gaming
- Support for long distance wireless links
- Reliable, continuous operation
- Cost-effective
- Power-effective

Wireless sensor networks consist of low-cost, low-power computer nodes with sensor devices and an ability to communicate wirelessly with other wireless sensor nodes. These nodes have dimensions in the tens of millimetres and are typically powered by AA (or smaller) batteries. Wireless sensor networks are designed for typical transmission ranges of up to a few hundred metres and bandwidth up to 250 kbps. Wireless sensor networks are an inappropriate solution for providing Internet access in rural areas because:

- A network solution would not be cost-effective because hundreds or even thousands of wireless sensor nodes would be required to establish a network.
- Bandwidth of 1 Mbps is not obtainable with wireless sensor networks.
- Wireless sensor networks do not support long distance wireless links.

- Wireless sensor networks are not designed for continuous transmissions. Continuous transmissions would drain the batteries and nodes would cease to function. Even with charging facilities, such as solar panels, it is unlikely that the batteries could be charged at a rate faster than they are being drained by the radio.

Satellites orbit the earth from 500–7,500 kilometres above the Earth's surface for low-earth orbit satellites [74], and at an altitude of 35,788 kilometres for geosynchronous orbit satellites [29]. One-way and two-way satellite Internet solutions exist. One-way operates by sending the signal from the users computer to the Internet service provider (ISP) using a dialup telephone connection. In the reverse direction, any data downloaded by the user is transmitted to the satellite and relayed back to earth to the user's location using a satellite modem and a receive-only dish. Two-way is more common than one-way and involves the satellite in both directions. The user has a satellite dish that is capable of both transmitting to, and receiving from, the satellite. The primary advantage of satellite networks is that Internet access can be provided nearly anywhere on Earth. Satellite networks can provide Internet access where no other Internet options are possible, such as on remote islands. However, in this thesis, satellite Internet is considered an inappropriate solution for providing Internet access to rural communities because:

- Satellite networks incur high latency ranging from 10 - 250ms [125]. These high latencies are inappropriate for interactive applications such as Skype and online gaming.

- Satellite networks suffer from rain fade and other atmospheric conditions. This means that bad weather can degrade or interrupt the satellite signal.

- Internet bandwidth is expensive and incurs strict data caps. These data caps are typically per day rather than per month and unused data does not rollover to the next day [58].

Cellular networks operate with a base station model where the base station costs tens of thousands of dollars but can serve a great number of users. The problem with cellular networks is that they are only cost effective for areas with high population densities. In sparsely populated areas, such as rural areas, there are not enough users to make the cellular approach economically viable.

Mesh-based solutions are cheaper than cellular networks but still suffer from issues with user density. Mesh networks are prone to interference and have a low throughput due to the number of hops involved. Mesh-based solutions are inappropriate for providing Internet access to rural communities due to the low density of users in rural areas and the costs involved.

Establishing long-range point-to-point networks in low-density areas is a cost-effective approach for wireless networks in rural areas. Most point-to-point technologies operate in the public spectrum and are low-latency. The availability of standardised wireless equipment such as ubiquiti [24] and meriaki [10] is increasing and new equipment is emerging all the time as wireless technology advances. The main advantage with point-to-point wireless technology is that it is low-cost; for example, ubiquiti devices cost a few hundred dollars. The point-to-multipoint equivalent of the technology is useful for areas of higher density, such as villages.

This discussion has shown that point-to-point is primarily the most appropriate wireless technology solution for providing Internet connectivity in rural areas. Point-to-point wireless networks are cost-effective and provide low-latency while delivering broadband data rates. For these reasons, point-to-point wireless technology, specifically 802.11 [35], has been selected for use in this thesis.

1.2 The CRCnet project

This section introduces the CRCnet project and describes how the project contributed to this thesis. The CRCnet project was a major inspiration and motivation for this thesis and identified that there was a need for broadband infrastructure in rural areas. The project shows that low-cost wireless technologies are viable for creating broadband wireless networks in rural areas and that rural communities are willing to be involved. The success of the CRCnet rural networks is largely dependent on community consultation and involvement. Familiarisation with the CRCnet project has helped the researcher to understand the wireless network planning process and identify important network planning lessons that were learned throughout the CRCnet project.

The following tells the story of the CRCnet project; firstly, to introduce useful terminology for this thesis by using the CRCnet infrastructure as examples; and secondly, to discuss the CRCnet networks and how the lessons that were learned from these networks contributed to this thesis.

The CRCnet (Connecting Rural Communities) project was started at the University of Waikato to investigate how best to provide Internet access to rural communities using low-cost wireless technologies. The group gained a greater understanding of how wireless networks operate in rural areas by building seven wireless networks over a period of ten years. Three of the networks are actually extensions of the original CRCnet network. The three extensions are: Te Pahu, Ngaroma and Eastern. The other three networks are the Hokianga, Rotorua and Tuhoe networks. The group also collaborated on wireless networks in South Africa, Samoa and the Solomon islands. The CRCnet project was recently commercialised and became Rurallink, showing that there is a legitimate need for broadband access in rural New Zealand. Now a fully-fledged ISP, Rurallink also operates the University of Waikato student wireless network and is establishing a wireless hot-spot presence in central Hamilton, New Zealand.

There are four components that that are used to construct the CRCnet networks: the solar relay, the powered relay, client premise equipment (CPE) and the Internet source. Relays transmit the wireless signal to other relays and to peoples homes. Most CRCnet relays are based on Soekris Technologies [19] small form-factor computers. Soekris computers have low DC power consumption, no moving parts and can support multiple radios. Figure 1.1 shows an example of a solar relay which is used where mains power is not available. Solar panels and rechargeable batteries are used to provide power to the relay. Solar relays have sufficient battery capacity to run for two or three days without charging so the site can still operate in cloudy weather. The powered relay can be mounted on a pole in a paddock, as shown in Figure 1.2(a) and power sourced from tens of metres away or the relay can be put on a building such as a shed or house to achieve the height advantage of being mounted on a pole but for less cost. A CPE is required for peoples homes to receive the wireless signal. The CPE is an integrated radio device designed for installation on houses. Figure 1.2(b) shows an example of a CPE.

Figure 1.1: Solar relay

(a) A powered relay

(b) Client premise equipment

Figure 1.2: Examples of a powered relay site and client premise equipment for a house site.

Kordia, New Zealand's state owned telecommunications company, provides the majority of Internet sources used in the CRCnet networks. Kordia provides national communication services for broadcast, telecommunications and specialized network solutions in New Zealand. Kordia owns a nationwide network of transmission towers, and has presence in major city buildings, that allow network operators such as CRCnet to install their own equipment and means that these transmission towers and buildings are potential sources for a wireless network. Figure 1.3 shows a comparison between CRCnet relays and major communication structures, including Kordia transmission towers, that can be found in New Zealand.

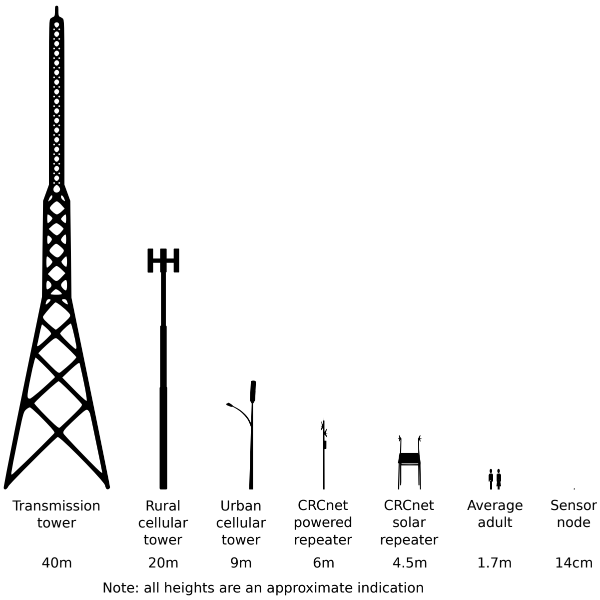


Figure 1.3: Height comparison of communication structures

In this thesis, a *site* is the particular location of an electronic communication device that is part of a wireless network. The term *source site* refers to the point of connection to the Internet, usually via an Internet service provider (ISP). The term *relay site* is used to refer to the solar relay and powered relay. The CPE is referred to as a *house site* though this may be another type of building such as a school. The term *house site* is used because the word 'house' is more meaningful to rural people than 'client premise equipment'.

A site consists of distinct parts; Figure 1.4 shows the parts for a solar relay site. Every site has at least one *antenna* that is responsible for converting electrical current to radio wave energy for transmitting and converting radio wave energy back to electrical current for receiving. A network *interface* card is a component that allows computers to connect to a network and communicate. Each wireless network *interface* card is physically connected to an *antenna*. A site will have at least one *host* which is a small, generally low-power computer that contains one or two network *interface* cards. The Soekris is a type of *host*. Solar sites also require *batteries* and a *solar controller* to manage the charging and use of the rechargeable *batteries*.

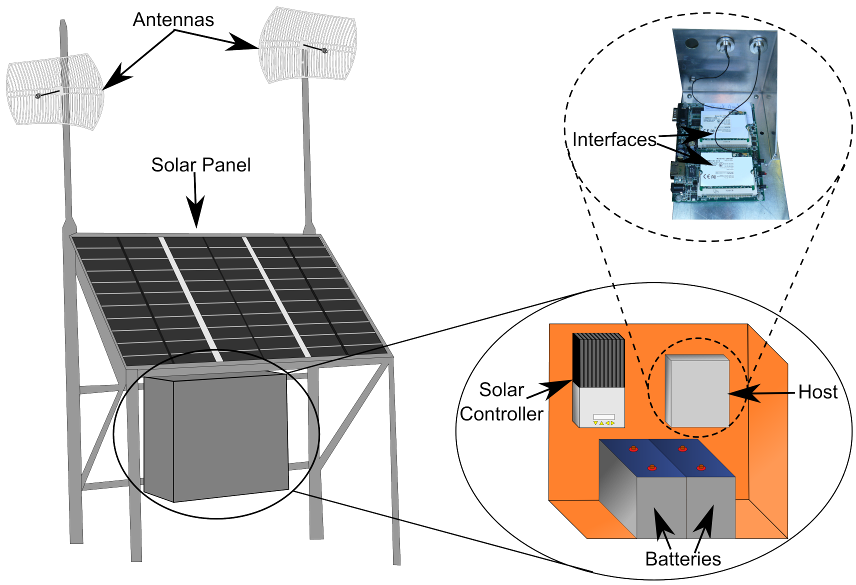


Figure 1.4: Parts of a solar relay site

A wireless *link* is a radio wave communications channel shared between two or more wireless sites. A *point-to-point (P2P)* link is a dedicated link that connects two wireless sites exclusively. A *point-to-multipoint (P2MP)* link is when one wireless site is connected to other wireless sites via a shared channel. A wireless access point providing Internet connectivity to multiple houses within a village is an example of point-to-multipoint. A *link profile plot* is a cross-section of the terrain between two connected sites. The *link profile plot* shows the terrain variation between the two sites as well as line-of-sight. Maintaining line-of-sight is important for the operation of wireless links as wireless technologies work poorly or not at all when line-of-sight is obstructed.

Network *connectivity* means that each site is connected to every other site in the network, either directly or via other sites, and ultimately, to the Internet. *Coverage* refers to the geographic area within which a wireless site can communicate. *Coverage plots* are used to visualise the coverage area. Coverage can also be expressed for the entire network–this is a union of each site's coverage area.

1.2.1 Established networks

This section discusses five of the CRCnet networks and the important lessons that were learned during planning and construction of these networks. The original CRCnet network is described, as well as three extensions: the Te Pahu network, the Eastern network and the Ngaroma network. The fifth network described is the Tūhoe network. Figure 1.5 shows the location of the CRCnet network (including extensions) and the Tūhoe network on a map of New Zealand.

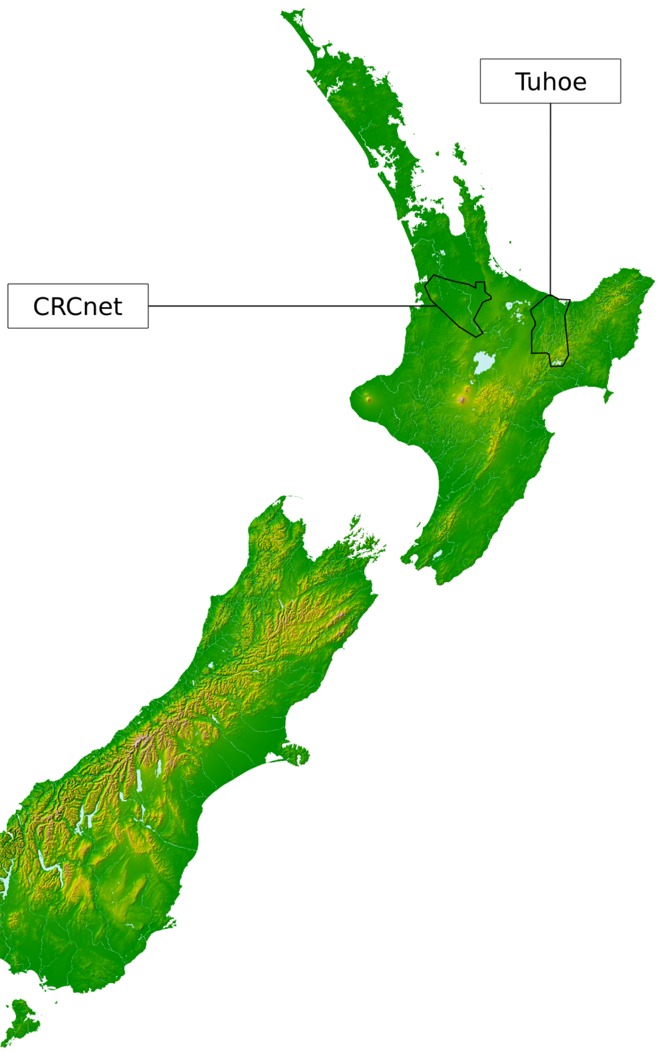


Figure 1.5: A map of New Zealand showing the locations of key networks.

1.2.1.1 The original CRCnet network and extensions

The original network was built to investigate how wireless networks perform in rural areas and to be a testbed for the development and testing of technologies and software. The original network extended from Hamilton to the west with its Internet source being the University of Waikato. The focus was to connect a number of schools, and homes of university staff, to broadband Internet. The network involved about 20 relay sites and the link of greatest length was 17 km. Rural schools involved were able to successfully video conference as a result.

Over subsequent years the network was extended to cover new areas. A small rural community, Te Pahu, was just beyond the original network. At the time the New Zealand Government was providing a broadband initiative fund and the Te Pahu community was granted part of this fund. An additional three relay sites were added to the existing network and now approximately 80 customers are connected to that part of the network. Another source was added for redundancy from one of Kordia's towers. The planner of the CRCnet network estimates that five days were spent in consultation with the Te Pahu community to plan this part of the network.

The network also extended to the east and to the south of Hamilton. The Eastern network added six relay sites and was sourced from the University of Waikato. The eastern network has approximately 80 customers and the longest link in the eastern area is 23 km. The Ngaroma network to the south was connected to the original network via a 42 km link and also to the eastern network, creating a loop. Five relay sites were added to connect approximately 42 customers in the Ngaroma area to the network. The planner of the CRCnet network estimates that seven days were spent in consultation with the Ngaroma community to plan this part of the network. Figure 1.6 shows the current structure and relative size of the CRCnet network including the three extensions.

The evolution of the CRCnet project is of particular motivational interest for this thesis. A number of valuable lessons have been learned with respect to wireless network planning including:

- CRCnet researchers noticed the quality of a link that cleared a group of trees a few years ago started to degrade. Investigation showed that the trees had grown taller and partially obstructed line-of-sight. The lesson here is that future vegetation growth needs to be anticipated when planning a link over or near vegetation. This would be particularly important if trees had only just been planted or if the landowner was planning on planting trees there in the near future.

- CRCnet researchers found that attempting to get physical access to a site at the back of a farm during winter proved to be quite difficult. The dirt track had turned to mud due to the winter rain and the 4WD vehicle could not get through the mud. The researchers had to return later once the track had dried out. This highlights the issue of accessibility to sites. It is important to know how a site should be accessed and how that access changes as a result of the weather and time of year. Sites cannot be built or maintained if they cannot be accessed.

- Livestock have chewed through CRCnet site cables and knocked equipment about. This illustrates the importance of adequately protecting cables and surrounding sites with fences.

- Lightning strikes can hit wireless sites and this has happened twice on CRCnet networks. Every wireless site should have a lightning rod to help protect the site against a lightning strike.

- Mains power is not available everywhere and so alternative energy sources are often required. It is important to know what the typical weather experienced at that site is like to make a decision about what alternative energy source is best.

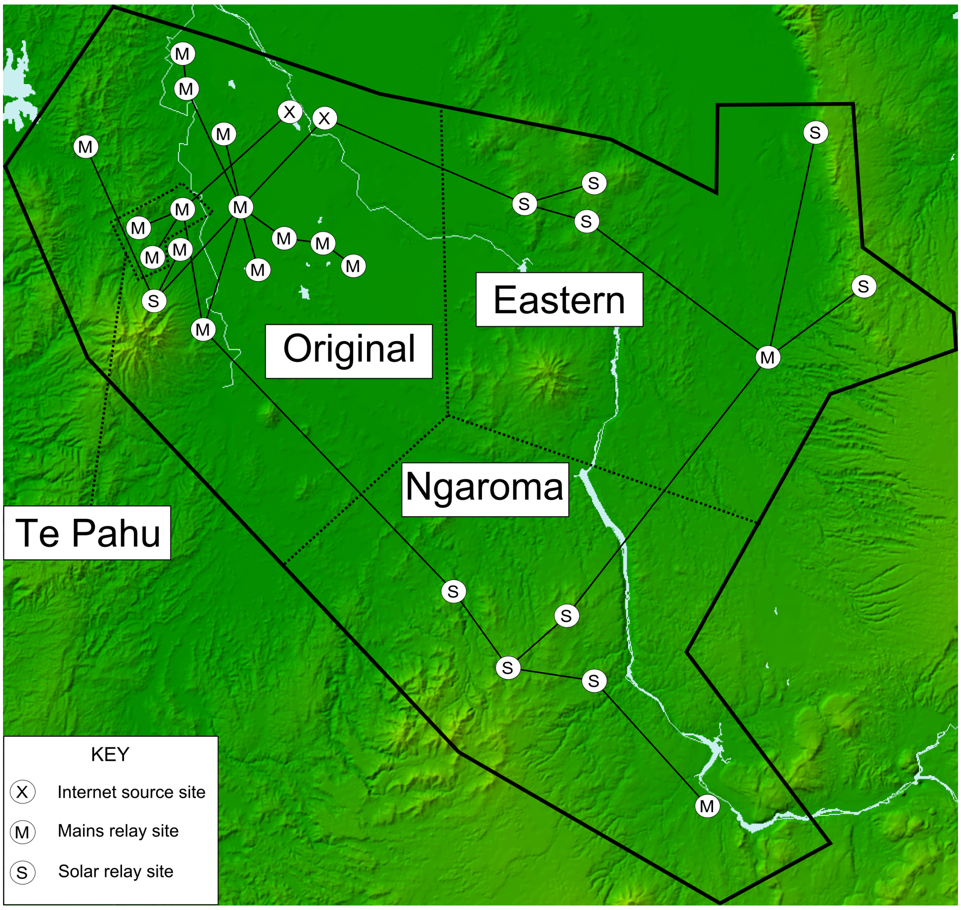


Figure 1.6: The current structure of the CRCnet network.

These valuable lessons have been applied to the planning tool presented in this thesis. Part of the CRCnet network is used for the tutorial used in the planning tool, which is discussed in Chapter 6.

1.2.1.2 The Tūhoe network

The Tūhoe network was originally built to connect four of New Zealand's most remote schools to the Internet. The schools were located in the mountainous Urewera National Park while the Internet source was a Kordia site 70 kilometres away from the nearest school. The Urewera National Park is a mountainous area with much of the terrain covered with vegetation. The area is sparsely populated, with the majority of residents living in isolated villages. The remoteness and rugged terrain of this area is of particular interest for this thesis and part of the Tūhoe network has been used to create the user study for this thesis, which is discussed in Chapter 9.

The network has since been extended to reach more schools and approximately 40 homes. Approximately 20 relays were required to construct the network and the longest link is 25 kilometres over mountainous terrain. The planner of the Tūhoe network estimates that 20 days were spent in consultation with the Tūhoe community to plan this network. Most of this time was spent consulting with iwi. Figure 1.7 shows the current structure and relative size of the Tūhoe network.

Thirteen of the relays in the network are solar-powered, each taking a team of three people a single day to build. Two of these solar sites required a helicopter to deliver all of the equipment due to their remoteness. One of the solar sites sits on the top of Mount Tawhiuau and is regularly dusted with snow during the winter months of the year. The construction of this network has had significant input from the local communities involved and it is now managed by Tūhoe Online, an ISP established by the local iwi.

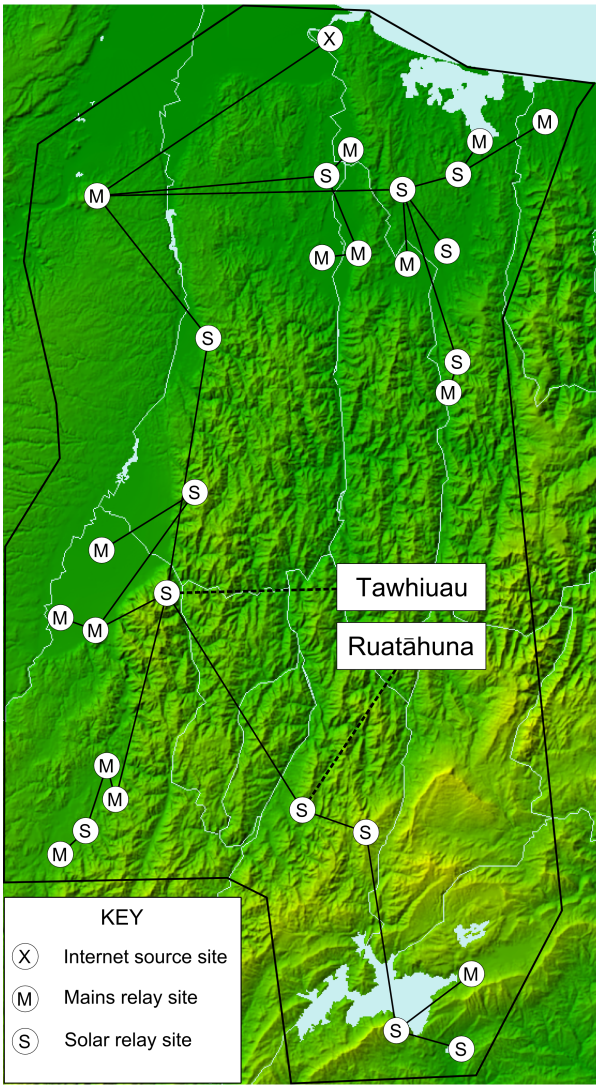


Figure 1.7: The current structure of the Tūhoe network.

The Tūhoe network highlighted the need and importance of cultural consultation and local knowledge for wireless network planning including:

- Natural features such as mountains, forests and rivers are important to Māori. Mountain summits are often a good choice for wireless sites however mountain summits may also be sacred to local Māori. This is the case with Mount Tawhiuau and by consultation with iwi, the site was built to one side of the summit. This raises the importance of consultation with local cultural experts to identify culturally significant areas. Another example of the importance of cultural consultation was when CRCnet researchers were faced with two similar trees blocking a potential link. After consultation with a cultural expert, they found that one of the trees was culturally significant and could not be touched but the other tree was not and so could be removed. Again, this shows the importance of consultation with local cultural experts to identify objects and areas that are culturally significant.

- CRCnet researchers discovered after constructing the Tawhiuau site, that at over 1000 metres in altitude, Mount Tawhiuau was often immersed in cloud. This created issues with receiving enough solar energy to sufficiently power the site. This was resolved by using larger batteries, though occasionally an extended period of cloudy weather will run the batteries flat and the batteries would then need to be replaced. Consultation with the community about typical weather conditions at the site would have helped identify these issues in advance and allow the site to be designed appropriately with the use of larger batteries, more solar panels and the possible consideration of wind power.

- Mount Tawhiuau has a walking track that is regularly used by people in the community. This is an important piece of local knowledge that indicates that there is adequate access by foot to the summit of Mount Tawhiuau and illustrates the importance of accessibility to a site.

1.2.2 Conclusions from the CRCnet project

The CRCnet project has identified the importance of community involvement in the planning of a wireless network. CRCnet researchers discovered that consultation with community members is vital for obtaining important information to assist with the planning of a wireless network. The researchers found that community involvement in planning the wireless network, as well as the building and maintaining of the network, can bring a number of social benefits to the community. The wireless network can be viewed as a community achievement and as an important social bond for the community.

CRCnet researchers realised that their wireless network planning expertise was only required for a small fraction of the time that they spent physically visiting an area as the majority of their time was spent exploring the area to determine what constraints exist. CRCnet researchers have investigated building wireless networks using commodity hardware and have discovered what works and what does not, allowing them to establish general construction guidelines for planning rural wireless networks. These general construction guidelines have simplified the wireless network problem to a point that it seems feasible to embed these guidelines within a software tool.

1.3 Problem statement

Currently, wireless network planning is lead by wireless network planning experts because these experts have intimate knowledge of the behaviour of wireless networks and how wireless networks are affected by physical environmental constraints. However, local communities have the best local knowledge of their area. This includes detailed knowledge of the physical environment as well as knowledge about culturally sensitive areas and potential social issues. The general construction guidelines established by the CRCnet researchers have simplified the wireless network problem to a point where it seems feasible to embed these guidelines within a software tool. This thesis hypothesises that such a software tool could be designed to enable members of rural communities to plan their own wireless networks.

This thesis examines the following question:

> Can a software tool be designed to assist members of rural communities with no expertise in wireless network planning, to plan a feasible wireless network?

The primary contribution of this thesis is that: the feasibility of designing a wireless networking planning tool that can assist members of rural communities with no expertise in wireless network planning, to plan a feasible network, has been established.

Current rural wireless network planning involves local community group meetings led by a wireless planning expert. The proposed solution envisions such meetings as still occurring but with software taking the place of the wireless planning expert. It is probably still necessary for several members of the local community to be involved collaboratively to obtain all the details about the local area that are required.

1.4 Research methodology

The following research questions can be derived from the main thesis question:

- How are wireless networks currently planned?
- What information is required and how is that information gathered?
- If a wireless network planning tool needs to be implemented,
  - How can the user interface of such a tool be designed and implemented such that it is suitable for collaborative use by non-expert community members?
  - How can the feasibility and adequacy of links be established?
  - Once the tool has been implemented, how can it be evaluated to determine if the thesis question has been answered?

1.4.1 How are wireless networks currently planned?

Wireless networks are planned by radio engineers conducting site surveys [16] and using analytical tools [121]. Depending on the scale of the network being planned and the wireless technology being used, software varies from online calculators [70] through to commercial software such as EDX and Mentum Planet [121]. The CRCnet group use Google Earth [8] and Radio Mobile [18] for wireless network planning; Johnson et al. recommend a similar approach [85]. Literature review of wireless community networks, such as those in India [113] and Latin America [73], and extensive consultation with the CRCnet group were used to investigate how wireless networks are currently planned.

It was established that there are a broad number of potential constraints from natural, human and technical sources. Analysis of existing wireless networks indicated that the size of the network was independent of the physical area covered and the number of constraints present in that area. Five key strategies for planning rural wireless networks were identified, including tasks and actions that occur as part of the planning process. Two methods for approaching planning problems were discovered; algorithmic planning and computer-assisted planning.

Further investigation discovered that algorithmic planning requires up-front knowledge of all possible constraints and is therefore inappropriate for addressing the entire rural wireless network planning problem. Computer-assisted planning bypasses this requirement of up-front knowledge of constraints. A review of twelve prominent wireless network planning tools was conducted to identify if any were appropriate for rural wireless network planning by non-expert community members, and to identify software and usability features that are important for wireless network planning.

1.4.2 What information is required and how is that information gathered?

Information required for wireless network planning, and how it is gathered, was identified by:

- consultation with the CRCnet group and in particular, learning from their previous experiences.
- visiting wireless site installations and observing the physical, social and technical factors that are involved.
- visually analysing photos and topographic maps of CRCnet networks.
- speaking informally with rural community members.

1.4.3 If a wireless network planning tool needs to be implemented,

Evaluation of the twelve prominent tools showed that no one tool was suitable for rural wireless network planning. Extending one of the existing tools was considered, however most of the tools were commercial and/or closed source, and a new user interface was required, it was decided to implement a new tool.

1.4.3.1 How can the feasibility of links be established?

There is extensive literature documenting radio wave propagation models which is explored in Appendix B. This literature was used to conduct a review of radio wave propagation models in Section 5.1 to establish which model or models were appropriate for radio wave propagation in rural environments. Once a model is chosen and that model has been used to predict propagation loss, the link budget formula that incorporates all gains and losses can be used to establish link feasibility. Utility programs were then able to be implemented that used these appropriate models with the link budget formula to calculate radio wave propagation attenuation and establish link feasibility. These utility programs are described in Section 5.2.

1.4.3.2 How can the user interface of such a tool be designed and implemented such that it is suitable for collaborative use by non-expert community members?

The use of personas is important, as potential end users would be difficult to have a available for repeated design and usability tests. These personas were accurately based on real people that the CRCnet group, and to a lessor degree the author, have consulted with. The author and members of the design feedback panel are from rural/farming backgrounds. Respect and understanding of cultural customs is important in both the development cycle and in the final software. The tool is intended to be operated by one user but to support collaborative use.

1.4.3.3 Once the tool has been implemented, how can it be evaluated to determine if the thesis question has been answered?

The tool can be evaluated with expert reviews and user testing. Expert reviews were conducted to evaluate usability and functionality. This included two usability expert reviews and one wireless network planning expert review. Expert reviews were conducted prior to user testing to identify usability problems that would prevent users from completing the planning process. Expert evaluation has a faster turn-around time than user testing and means that usability problems could be quickly identified and addressed before progressing to user testing.

The usability expert reviews were a mix of heuristic evaluation with a cognitive walk-through. The two usability experts independently used the WiPlan software by following the tutorial and experimenting with the interface. Each expert evaluated the interface against Nielsen's heuristics and identified usability problems by heuristic. Issues from the first usability review were addressed before the second review took place. The wireless network planning expert also used the WiPlan software by following the tutorial and experimenting with the interface. The expert commented on the user interface and functionality.

Two user study evaluations took place in groups of five where each person role-played a persona. Role-playing was used as a real meeting that could be observed is impractical. A real meeting may take place over more than one day. Rural communities are typically isolated from urban areas and it would be difficult to get real people together in one place at one time, as farmers in particular are very busy people. Real people from an area where a wireless network already exists may also be biased by the existing network. The advantages of role-playing means that an area with an existing network that is known to the researcher can be chosen where the situation is fully understood and the presence of an existing network shows that a viable solution exists.

1.5 Research contributions

The research in this thesis makes the following original contributions:

- A review of widely-used existing wireless network planning tools, identifying features that a planning tool for use by non-expert rural communities should support, and identification of five strategies for wireless network planning.

- An methodology for identifying natural, human and technical constraints that affect rural wireless network planning. Natural, human and technical constraints were identified in a New Zealand context and the effect of those constraints on rural wireless network planning was analysed.

- A novel HCI study design, structured as a role-playing game, for evaluating cooperative planning software, and a demonstration of its effectiveness for use when the target end users were difficult to attain.

- The proposed software tool was actually built and was fundamental for the aforementioned novel role playing game evaluation.

1.6 Thesis outline

This thesis is multi-disciplinary, drawing on and contributing to work in the areas of radio wave propagation, radio regulations, wireless computer networks, rural deployment, computer-aided planning, user interfaces and algorithms, usability evaluation, rural communities and socio-technical issues. Because of this diversity, there is no single literature review chapter in this thesis. Instead, review of other work in the areas concerned is presented in the relevant chapters. Specific chapters that review literature include Chapter 3, Chapter 5, Chapter 6, Chapter 8 and Chapter 9. Requirements elicitation is also spread over many chapters in this thesis. Design requirements are explicitly defined in a double-framed box as they are identified. Requirements identified in a particular chapter are summarised at the end of that chapter. All of the design requirements are then summarised at the beginning of Chapter 6.

Chapter 2 establishes that wireless network planning is non-trivial by discussing the range of issues that need to be considered. These issues include the complexity and scale of the wireless network planning problem and the broad range of constraints that affect wireless network planning. The chapter then introduces five strategies that can be used for planning wireless networks. These strategies are relevant in the user trials discussed in Chapter 9.

Two approaches to wireless network planning are presented in Chapter 3: algorithmic planning; and computer-assisted planning. Each of these approaches is described and literature relevant to the approach is reviewed. The chapter concludes with a review of twelve existing computer-assisted planning tools and identifies features that a planning tool should support.

Chapter 4 discusses the types of information that are required for planning a wireless network and how these types of information can be obtained. The chapter describes information regarding the natural environment, climate and the human environment.

Chapter 5 discusses the key issue of link feasibility analysis in wireless network planning and describes the WiPlan approach for determining link feasibility.

Chapter 6 introduces the use of personas and how they were used in the development of WiPlan. The chapter then describes the user interface design of WiPlan and finally the WiPlan system is subjected to the same analysis as the existing planning tools described in Chapter 3.

Chapter 7 discusses the implementation of WiPlan, describing the development environment and the internal architecture of WiPlan.

In Chapter 8, WiPlan is reviewed by three experts. This chapter explains how the reviews took place and what the findings were.

Chapter 9 discusses the methodology of how the user study evaluations were conducted, presents the results and discusses the implications of these results for WiPlan.

Finally, Chapter 10 concludes this thesis and suggests future research directions.

Chapter 2

Planning wireless networks

This chapter describes the complexity and scale of planning wireless networks and discusses the broadness of the constraints involved. Planning a wireless network requires decisions about where to place sites and establish links between sites. The complexity and scale of planning a wireless network means that it is important to have a strategy to follow. This chapter presents five different strategies for the planning process and details the tasks required in following any of the strategies.

2.1 Complexity and scale

The complexity and scale of the wireless network planning problem is interesting because the solution size remains almost constant independent of the physical area and multiple constraints being searched. For example, consider the CRCnet networks discussed in Section 1.2.1. Table 2.1 shows the approximate geographic area covered by three of the CRCnet networks and the number of relays present in each. The table shows that the approximate geographic area only has a small influence on the number of the relays in the solution.

Network	Approximate geographic area	Number of relays in solution
Hokianga	200 km^2	5
Tuhoe	3700 km^2	20
CRCnet	5000 km^2	35

Table 2.1: Number of relays vs geographic area

Many wireless networks, cellular networks in particular, have a pre-defined set of candidate locations for sites. Consider an example network being planned with a set of n candidate locations. The number of links to be explored is related to the number of sites by the formula $\frac{n(n-1)}{2}$. Where there are no candidate locations, every possible point in the area being considered is a candidate location. The area of the considered example network is 100 kilometres by 100 kilometres. The resolution of the terrain data comes in to play here; resolutions of 1000 metres, 100 metres and 25 metres are considered for this example as these resolutions are typical of available terrain data. Table 2.2 shows the number of links that need to be explored in terms of these factors, ignoring any configuration complexity. It is clear that the search space is much more difficult to explore when there are no known candidate sites. This indicates that any kind of brute force attempt at exploring a search space of this size will require excessive amounts of computer memory and time.

Terrain resolution	No. of candidate sites	No. of links to explore
NA	10	45
NA	100	4950
NA	1,000	4.995×10^5
1,000 m	10,000	4.9995×10^7
100 m	1,000,000	4.999995×10^{11}
25 m	160,000,000	1.28×10^{16}

Table 2.2: Exploring the search space

2.2 Broadness of constraints

Wireless network planning constraints span a broad range of environments. Constraints can be categorised as: natural, such as terrain; human, such as cultural sites; and technical, such as frequency. These constraints either affect the placement of sites or the creation of links. The effects of these constraints can often be mitigated; for example, the antennas of an obstructed link can be raised so that the link is line-of-sight. However, some constraints can not be mitigated and therefore the affected site or link is removed from consideration.

Constraints affect wireless network planning in different ways. It is a complex task to identify and locate these constraints in the local area. The problem is that it is difficult to acquire information on all the constraints globally in an easy way. The sheer volume of data that would be required to store the broad range of constraints for the entire geographic area being considered would be very large.

The source of constraint data is the main problem. Some geographic data is available digitally with varying degrees of quality. Knowledge of the majority of constraints are however only found in the minds of a diverse group of people within the community. These people know where constraints are and the significance of the constraints in the community, though they may not know how the constraint affects wireless network planning. The precision and accuracy of the knowledge of constraints may vary and other constraints can vary and be prone to change.

Table 2.3 lists the constraint classifications by category that have been identified through the CRCnet experience. Each classification of constraint consists of several features; for example, hydrological consists of features such as rivers, streams, lakes, swamps, wetlands and the coast. Examples of each constraint category are given to illustrate the broadness of these constraints. Further explanation of the effect that natural and human constraints have on wireless network planning are covered in Chapter 4. Technical constraints are referred to throughout the thesis, though most of the technical constraints are further described in Chapter 5.

Natural constraints	Human constraints	Technical constraints
Terrain	Transportation infrastructure	Line-of-sight
Hydrological	Utilities	Link distance
Vegetation	Buildings	Link frequency
Animals	Theft/vandalism	Radio selection
Weather	Cultural	Antenna selection
	Social	Link capacity
	Safety	Power consumption
	Power availability	Site construction

Table 2.3: Broadness of constraint classifications

Terrain is a classification example of a natural constraint. Terrain exists in different forms and affects wireless network planning in different ways. Terrain primary affects the cost and access of a site as well as being a contributing factor to deciding whether to place a site at a given location. As an example, the Tawhiuau site in the Tūhoe network is at an elevation of 1000 metres. Though a walking track exists, it takes approximately two and a half hours to walk to the site. A helicopter was required to deliver the materials for building the site. The batteries have had to be replaced twice for this site and both times the batteries have been delivered by helicopter.

Cultural issues are a classification example of a human constraint. The primary cultural issue is respect of culturally significant objects and areas. Certain objects may affect a wireless link however these objects may be culturally significant. For example, when building the Tūhoe network, the CRCnet team were trying to establish a wireless link where a tree was obstructing line-of-sight. After speaking to the cultural representative, they found that it was fine to remove the tree. However, they were told that a similar tree, only a few metres away, was culturally significant and could not be touched. Areas that are culturally significant may prevent sites from being built in those areas. For example, in New Zealand, Māori people regard prominent mountain summits as sacred; these sacred mountains should be respected by not building sites on those sacred summits.

Site construction is an example of a technical constraint. The construction of a site needs to protect the equipment from weather and animals while supporting the antennas and other equipment. The CRCnet project has addressed the issue of site construction with their solar and powered relay site solutions. However in some situations, these site solutions may require adjustment, such as in areas that experience high winds.

> *Requirement 1:* a planning tool should solicit information about natural, human and technical constraints.

2.3 Strategies for the planning process

This section describes a range of planning strategies that people might use to plan a wireless network. One of these strategies, the reverse-branch, is the strategy that the CRCnet researchers employ for planning their wireless networks [106]. The other four strategies include: mesh, direct, forward-branch and multi-branch. Discussing these five strategies shows that there are different strategies that people might use and that different strategies can apply to different types of network planning problems. Identifying these strategies also provides a means of evaluation for the study trials described in Chapter 9. Constraints can be considered at any point in the strategies and therefore are not explicitly referred to in the discussion of strategies. The discussed strategies could be performed by hand, algorithmically or a blend of the two (computer-assisted planning).

> *Requirement 2:* a planning tool should support the use of all five of the network planning strategies.

2.3.1 Mesh strategy

The mesh strategy involves creating a mesh of links between sites and then progressively eliminating links and sites. Figure 2.1 shows an example of how to use the mesh strategy. Firstly, all of the source and house sites are created. The area is then explored to identify possible relay site locations, such as elevated locations, where relay sites are subsequently placed. Links are then established between the sites so the house sites and source site are connected via relay sites. The process of site/link elimination can then begin.

There are several ways of eliminating sites and links from consideration. In some cases, there will be a subset of line-of-sight links that connect the house sites to the source site via relay sites. Any non-line-of-sight links and associated relay sites are removed to leave the network solution.

One method of eliminating sites and links from consideration would be to compare the cost of relays and repeatedly remove the most expensive relay site until a solution is reached. This may require height adjustment of some relay antenna heights to ensure line-of-sight links. Cost of relays should be contrasted with the ease of access to a site, as a cheap site may be difficult to access and vice-versa.

Often the elimination stage will reveal that there is not a complete solution using the initial set of relay sites. In these cases, it is necessary to repeat the process by placing relays in the areas where there are no viable links, creating more links and removing by elimination.

2.3.2 Direct strategy

The direct strategy guarantees a solution but is likely to be inefficient for rural areas as the solution will have an excessive number of relays. Figure 2.2 shows an example of how to use the direct strategy. Firstly, all of the source and house sites are created. Secondly, the source and house sites are connected using direct links. Thirdly, antenna heights are adjusted where possible to create line-of-sight links.

Finally, for any links that are still non line-of-sight, a relay site is added at the point in the link profile where line-of-sight is most significantly breached. This means finding the highest hill that is blocking line-of-sight and placing a relay site at the top of it. The non line-of-sight link can then be removed and replaced with two new links, one of which needs to be line-of-sight to progress towards a solution.

A solution will eventually found by repeating this method of adding relays to non line-of-sight links. There is minimal area exploration involved in this strategy and therefore this strategy tends to yield poor, and often expensive, solutions.

2.3.3 Forward-branch strategy

The forward-branch strategy involves starting with the source site and branching towards the house sites. Figure 2.3 shows an example of how to use the forward-branch strategy. Firstly, all of the source and house sites are created. The forward-branch strategy starts with the source site, which is denoted the current site. The area around the current site in the direction of the house sites is explored to find possible relay site locations. Once suitable relay site locations have been found, a relay is placed at each location and a link between each relay and the source is established. This may require height adjustment of some relay antenna heights to ensure line-of-sight links. Relay sites are then eliminated based on site access and cost until one relay remains. This relay then becomes the current site and the forward-branch strategy is repeated until the source site is connected to all of the house sites via relay sites.

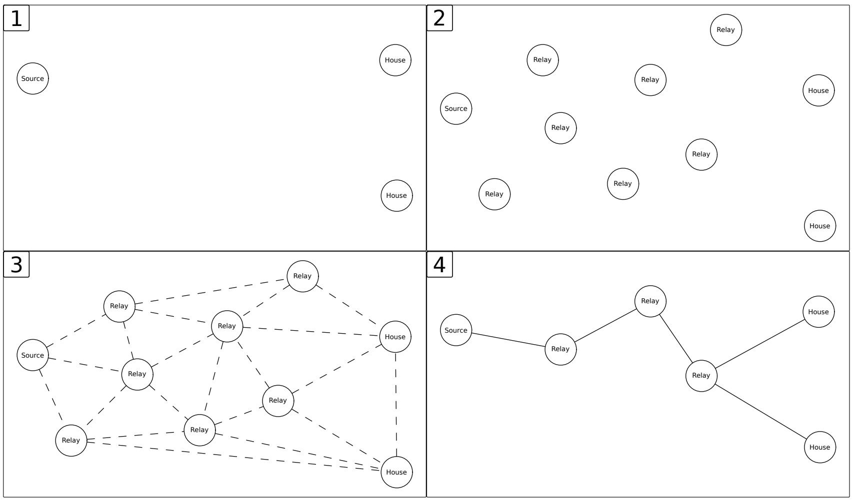


Figure 2.1: Example of the mesh strategy

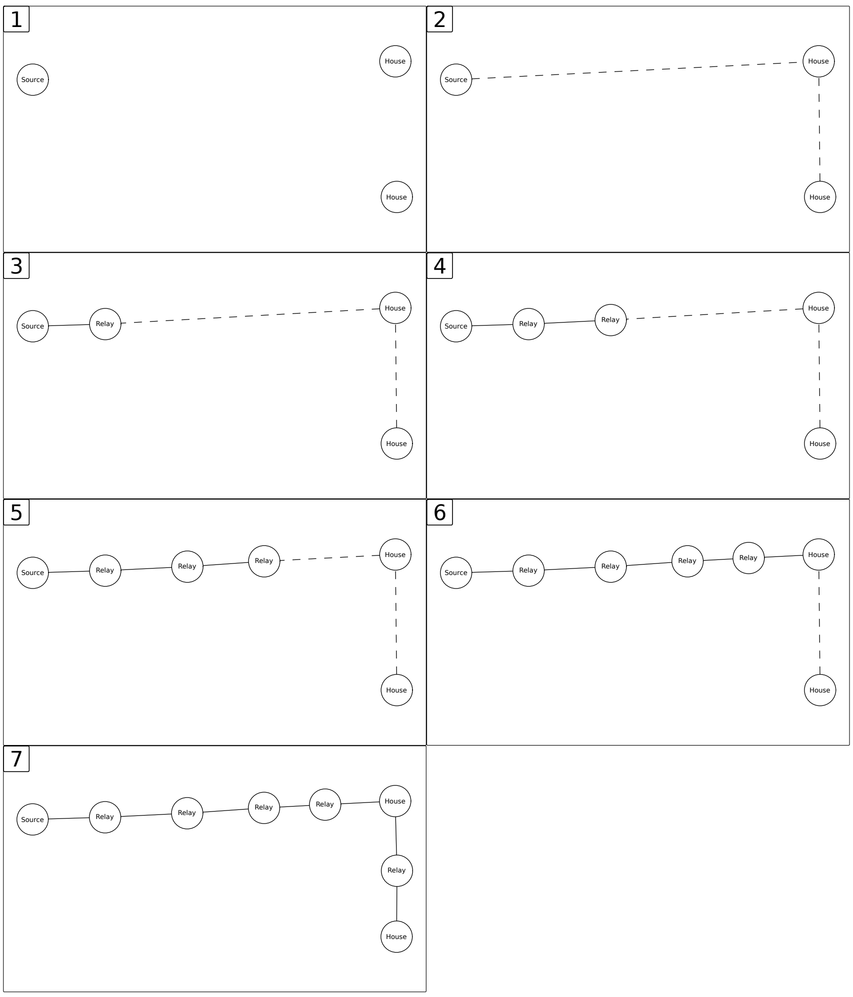


Figure 2.2: Example of the direct strategy

2.3.4 Reverse-branch strategy

The reverse-branch strategy was used for planning the CRCnet networks [106]. Figure 2.4 shows an example of how to use the reverse-branch strategy. Firstly, all of the source and house sites are created. The reverse-branch strategy starts with the house sites and works backwards to the source site. The focus is to firstly connect the house sites together using relay sites and then secondly focus on connecting the house sites to the source site. The area around the house sites is explored to find possible relay site locations for the house sites to connect to. Once suitable relay site locations have been found, a relay is placed at each location and a link between each relay and as many house sites as possible is established. Some relay antenna heights may require adjustment to ensure line-of-sight links.

Relay sites are then eliminated based on site considerations until the minimum number of relays remains. The minimum number of relays is the number of relays required to connect all of the house sites to at least one relay. Once this has been achieved, the focus turns to connecting these relays to the source. The area around each relay in the direction of the source site is explored to find further possible relay site locations. Relay sites are then placed at these locations and links are created between as many of the relays as possible. The new relay sites are then eliminated based on site access and cost until ideally one relay remains. In some cases, house sites may be far apart and several iterations of the reverse-branch strategy may be required before only one new relay is required to connect all of the previous relays. The reverse-branch strategy is repeated until all of the house sites are connected to the source site via relay sites.

2.3.5 Multi-branch strategy

The multi-branch strategy is best used when there is a single large tower or hill that overlooks much of the surrounding area. Figure 2.5 shows an example

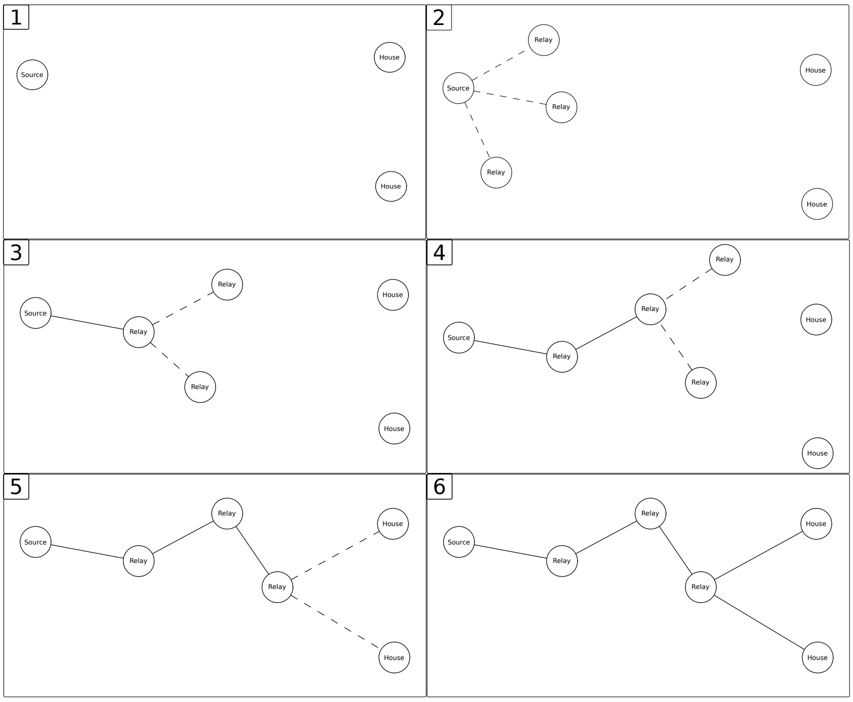


Figure 2.3: Example of forward-branch strategy

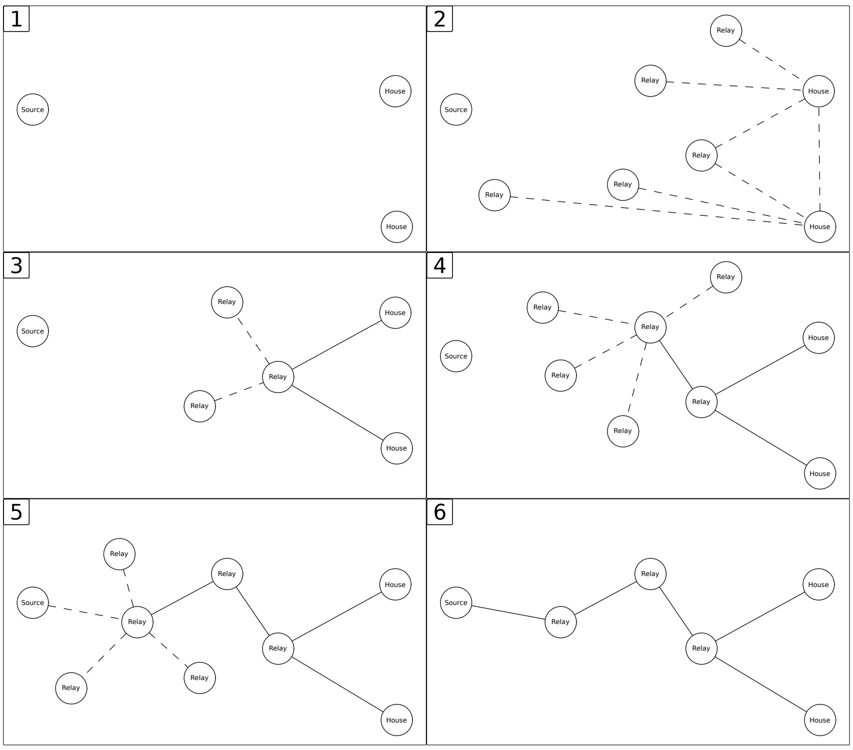


Figure 2.4: Example of reverse-branch strategy

of how to use the multi-branch strategy. Firstly, all of the source and house sites are created. The focus is then to find a single relay site that is elevated above the rest of the terrain. Once the relay site has been placed at this high elevation, further relay site locations can be explored in the direction of both the source and the house sites using either the forward-branch or reverse-branch strategies. In some cases, direct links to the source and/or house sites may be possible. Typically, links will branch out from the relay site in two directions but more branches may be required if the house sites are well dispersed. Focus can be on one branch at a time or one relay at a time for each branch before looking at the next branch. Some relay antenna heights may require adjustment to ensure line-of-sight links.

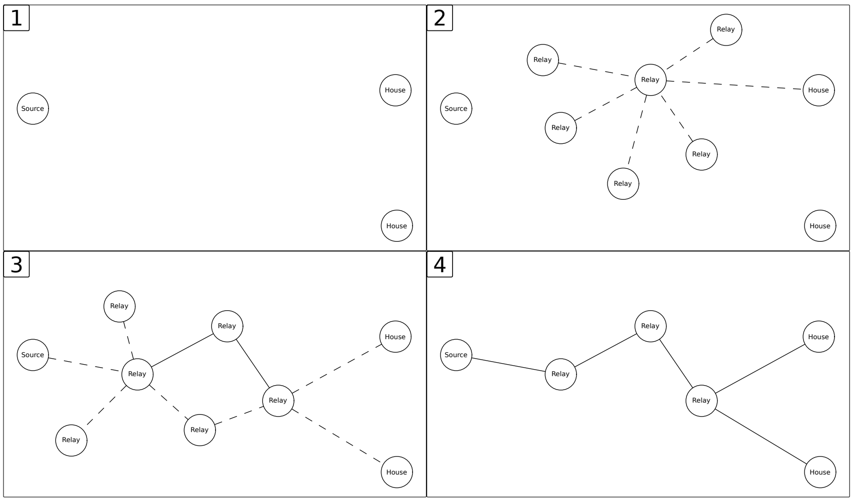


Figure 2.5: Example of multi-branch strategy

2.4 Planning tasks and actions

This section explains the tasks that take place as part of the wireless network planning processes discussed in Section 2.3. These tasks can be derived by considering the following three observations paraphrased from the observations by Sen and Raman [113]:

O1 Antenna heights, antenna types, and transmit powers are all dependent on the network topology

O2 Antenna heights are independent of the antenna types or the transmit powers, as antenna heights ensure that there is line-of-sight

O3 Antenna types and transmit powers are directly dependent on one another.

Observation O1 suggests that the primary objective in wireless network planning is to establish a network topology. Establishing a network topology is in fact two tasks in itself; Task 1 (T1) is to determine the placement of sites and Task 2 (T2) is to create links between the sites.

Since tower heights are independent of the antenna types and the transmit powers, and are chosen simply to ensure line-of-sight, Task 3 (T3) is to establish line-of-sight for each link by adjusting antenna heights at either end of the link. Once line-of-sight has been established, antenna types and transmit powers can be determined. The use of 802.11 protocols largely implies that the antennas determine the transmit power and so effectively the determination of antenna types and transmit powers are solved together and are incorporated within Task 3.

Typically Task 1, Task 2 and Task 3 are carried out in sequence but once this sequence has occurred once, these tasks can be carried out in any order (at least two sites must exist to create a link and a link must exist in order to establish line-of-sight).

T1 Placement of sites

T2 Creation of links

T3 Line-of-sight establishment

There are five actions that a user can perform to accomplish these tasks. Some actions only achieve part of a task while other actions can complete more than one task.

Action 1 (A1) is choosing a location for creating a site; it is useful to give the created site a relevant name so it can be easily identified, Action 2 (A2) is therefore naming a site. Both Action 1 (A1) and Action 2 (A2) are regarded as part of Task 1 (T1).

Action 3 (A3) is the setting and adjusting of antenna heights which can be regarded as being part of Task 1 (T1) or Task 3 (T3) depending on implementation. For example, a site may be created that has a four metre pole for mounting antennas on (T1). However, a particular link may require the antenna to be five metres high (T3), in which case the pole height may be revisited.

Creating a link/conducting point-to-point analysis is Action 4 (A4) and computing coverage/conducting point-to-multipoint analysis is Action 5 (A5). Action 4 (A4) and Action 5 (A5) achieve completing Task 2 (T2) and often Task 3 (T3) also. For example, the user may create a link and establish line-of-sight of that link in sequence (T2 and T3). Otherwise, the user may revisit the link at a later stage and adjusts the antenna heights (A3) to establish line-of-sight (T3).

A1 Choosing a location for creating a site (Part of T1)

A2 Naming a site (Part of T1)

A3 Setting/adjusting antenna heights (Part of T1 or T3)

A4 Creating a link

A5 Computing coverage

Requirement 3: a planning tool should support all of these tasks and actions.

2.4.1 Planning action context

This section describes the context in which each planning action is performed, discussing such issues as when the action is performed, how difficult the action is and what information is required to perform the action.

A1 - Choosing a location for creating a site A site can be created at anytime by anyone with knowledge about constraints in the local area. This is achieved by deciding on a suitable location that is not subject to constraints such as those identified in Section2.2. This action is of medium difficulty, as it requires extensive local knowledge to identify constraints; however community collaboration can help with identifying constraints and reduce the difficulty involved.

A2 - Naming a site A site can be given any name by anyone, though the site must first exist. The site should be given a sensible and relevant name, for example the landowners' surname. The only difficulty with this action is obtaining the name of the landowners, though this should be easily obtainable through local knowledge and community collaboration.

A3 - Setting/adjusting antenna heights Antenna heights can be set and adjusted once a site exists and usually takes place in conjunction with creating a link (Action 4) otherwise the antenna heights may need adjusting. The action of setting or adjusting the height of an antenna is not difficult but often relies on the outcome of creating a link (Action 4).

A4 - Creating a link Creating a link requires at least two sites to exist and can be a difficult action to perform, as it requires a complex understanding of line-of-sight and mathematics, as well as identification of constraints that may affect line-of-sight. Local knowledge and community collaboration can assist with identifying these constraints. Technical understanding of radio wave propagation, radio hardware and antenna is required to determine line-of-sight. However in some situations, where there are few constraints and short distances involved, links can be created through trial and error fairly easily using visual line-of-sight as a guide.

A5 - Computing coverage Computing coverage requires a site to exist and is dependent on the antenna height being set. As with creating a link, computing coverage requires complex technical understanding and identification of constraints that may affect line-of-sight. Once again, local knowledge and community collaboration can assist with identifying these constraints.

2.5 Chapter summary

This chapter has described the complexity and scale involved in the wireless network planning problem and discussed the broadness of constraints that need to be considered. The complexity and scale of planning a wireless network means that it is important to have a strategy to follow and therefore this chapter has presented five different strategies for planning wireless networks and detailed the tasks required. The actions required to achieve these tasks were identified and the relative context of those actions were described.

The following requirements for a planning tool were identified:

- a planning tool should solicit information about natural, human and technical constraints (Requirement 1).
- a planning tool should support all of the network planning strategies identified in Section 2.3 (Requirement 2).
- a planning tool should support all of the tasks and actions identified in Section 2.4 (Requirement 3).

Now that wireless network planning has been described in more detail, it is appropriate to discuss high-level methods of how to solve the wireless network planning problem. The next chapter introduces two high-level methods for planning a wireless network: algorithmic planning and computer-assisted planning.

Chapter 3

Computer-assisted planning

This chapter establishes why computer-assisted planning is the best method for planning a wireless network by contrasting computer-assisted planning with algorithmic planning. Algorithmic planning is explained including a literature review of how algorithmic planning is used to solve sub-elements of the wireless network planning problem. However, algorithmic planning requires up-front knowledge of all possible constraints and is therefore inappropriate for addressing the entire wireless network planning problem. The chapter describes how computer-assisted planning allows constraints to be addressed as they are identified by the user. A review of twelve existing computer-assisted planning tools identifies the features supported by each of the tools with a primary focus on how each tool incorporates local knowledge and how the user is supported in planning a wireless network.

3.1 Algorithmic planning

Algorithmic planning uses algorithmic optimisation or approximation techniques to find the best possible solution relative to one or more objectives with a set of data subjected to a set of constraints. Usually the objective is to minimise or maximise one (or more) data parameters such as time, distance or cost.

Algorithmic planning is an active area of research in the field of telecommunication network planning. Algorithmic planning techniques that have been applied to telecommunication network planning include meta-heuristics [43, 57, 69, 88, 92, 120], linear programming [44, 93, 95–97] and geometric approaches [56, 91, 116].

Meta-heuristic optimisation is a computational method that iteratively works to improve a solution or set of solutions using some function of quality but is not guaranteed to find an optimal solution. Meta-heuristics are used for a variety of combinatorial problems and include such techniques as simulated annealing [43, 92, 120] and genetic algorithms [43, 57, 69, 88, 120]. Hill-climbing performs well as a quick search for local optima but cannot identify global optima [43].

Linear programming is a mathematical method applied when the solution search space can be expressed as a set of linear constraints. The objective is to find the minimum or maximum value of a linear function that may consist of many parts, subject to a set of linear constraints. Linear programming theory falls within convex optimization theory and is an important part of operations research [71]. In cases where some, or all, variables are restricted to integers; variants of the approach referred to as integer linear programming or mixed integer programming [54] are used. It is also possible for equations to be non-linear (nonlinear programming [119]). Linear programming is used extensively in business and economics, but can be useful in areas such as transportation, energy, telecommunications, and manufacturing.

Other algorithmic planning techniques used in literature for telecommunication network planning include the use of Gaussian Processes [91], Steiner trees [56] and Voronoi tessellations/Delaunay triangulation [116].

3.1.1 An algorithmic planning example

A relatively simple diet problem, as described by Pedregal [107], is used to illustrate the inputs necessary for an optimisation algorithm and how those inputs can be represented in an algorithmic way. The required data can be determined once the objective and constraints are known. This discussion is based on the optimisation example that Pedregal presents on page 10 of *Introduction to Optimization* [107]. Pedregal's diet example is presented below with discussion about how the problem can be expressed algorithmically.

- The objective is to minimise the total cost of the diet.
- The single constraint is to meet the minimum daily requirement for each nutrient
- The data includes:
  - food types and their respective prices
  - daily minimum requirements of each nutrient
  - nutrient content for each food

The objective, constraints and data need to be expressed so that they are appropriate for algorithm input. Note that, for this discussion, arrays are considered to be equivalent to matrices.

Consider the set of food types and their respective prices. This could be expressed as two arrays where each index, i, of the two arrays represents one type of food. The first array, x, stores the amount of each food type purchased and the second array, c, stores the price of each food type. For example, x_i is the amount of food type i purchased for unit cost of c_i; an example is given in Table 3.1.

Consider now the set of daily minimum requirements of each nutrient. This could be expressed as a single array, b, where each index, j, represents a required nutrient. For example, b_j represents the daily minimum requirement of nutrient j.

Finally, consider the nutrient content that each food contains. As there are multiple foods and each food has multiple nutrients, this will need to expressed as a two-dimensional array, a. Index i represents a particular food and index j represents a particular nutrient content. For example, a_{ij} represents the content of nutrient j in food i.

The objective and associated constraints can now be defined in algebraic terms. Knowing that the total cost of food purchased needs to be minimised, the objective can be expressed as:

$$Minimise \quad \sum_i c_i x_i$$

Also, knowing that the daily minimum requirement for each nutrient must be met, the constraint can be expressed as:

$$\sum_i a_{ij} x_i \geq b_j \qquad for\, all\, j$$

Note that there is a second constraint that was not immediately apparent before. The second constraint needs to enforce that all quantities of food must be positive and is expressed as:

$$x_i \geq 0 \qquad for\, all\, i$$

The diet optimisation problem has been expressed in algebraic terms by Pedregal [107] and is suitable for algorithmic input. However stepping through this optimisation problem has shown that detailed knowledge and a complete corpus of information is required to fulfill the data requirements. It is critical that the data is as accurate as possible and it is difficult to represent vague criteria in an algebraic form.. The data requirements of this relatively simple problem highlight the issue of data volume requirements and that it would be difficult to represent every constraint in an algorithmic way.

	Chocolate	Steak	Beans	Carrots	Bacon
Array x	? g	? g	? g	? g	? g
Array y	$1.00/100g	$3.50/100g	$0.30/100g	$0.50/100g	$1.75/100g

Table 3.1: Example of food types and prices

Nutrient	Required Amount
Magnesium	400 mg
Zinc	15 mg
Potassium	3500 mg
Calcium	1000 mg
Iron	18 mg

Table 3.2: Example of daily minimum requirements

		Food type (100 g)				
		Chocolate	Steak	Beans	Carrots	Bacon
Nutrient level	Magnesium	146 mg	28 mg	18 mg	10 mg	30 mg
	Zinc	2.01 mg	5.55 mg	0.25 mg	0.17 mg	3.36 mg
	Potassium	559 mg	406 mg	146 mg	237 mg	539 mg
	Calcium	56 mg	12 mg	44 mg	32 mg	10 mg
	Iron	8.02 mg	3.42 mg	0.65 mg	0.89 mg	1.49 mg

Table 3.3: Example of nutrient content per food type

3.1.2 Algorithmic planning literature

Algorithmic planning has been used to address many sub-elements of the wireless network planning problem such as base station placement for cellular networks, coverage maximisation and sensor placement. There are two key themes that have been identified in the literature: energy efficiency and coverage.

3.1.2.1 Energy efficiency

The first theme observed in the literature is energy efficiency. The primary intention is to maximise the energy efficiency, often referred to as the lifetime, of a network while meeting other objectives. A common objective in wireless sensor networks is to maximise the lifetime of the network while also maximising the sensing coverage of the network. Genetic algorithms [69, 88], Gaussian Processes [91], simulated annealing [92] and nonlinear programming [67] approaches have been utilised to explore energy efficiency solutions. These approaches all assume that a set of candidate locations is available.

Another common objective is to ensure that coverage or connectivity constraints have been met. Semidefinite programming [62] and integer programming with a Lagrangian relaxation technique [124] approaches are used to maximise energy efficiency but ensure that the connectivity constraint is met in wireless local area networks. A genetic algorithm was used by Chiara et al. [57] to maximise energy efficiency while ensuring coverage in mobile networks.

3.1.2.2 Coverage

The second theme observed in literature is coverage. The primary intention is to maximise or meet coverage constraints of a network while meeting other objectives. The most common objective identified in the literature was maximising/meeting coverage while minimising the number of the stations/relays or minimising the network cost. Effectively minimising the number of stations/relays is minimising the cost of the network, so these are categorised as the same objective. Gondran et al. [76] present a model that thoroughly defines all major parameters met in wireless network access point planning problems along with a didactical explanation of an indoor wireless network. The objective is to minimise the total cost of the network subject to the constraints of ensuring all demand points are covered to an agreed signal level and that the number of base stations does not exceed a given threshold. Maximising coverage while minimising cost is common theme for literature concerning cellular networks and literature shows that variations of linear programming is the typical approach used [44, 93, 96, 97].

Other objectives involve maximising coverage while meeting other constraints. Mateus et al. [95] use integer programming to to maximise coverage of an indoor local area network subject to a set of constraints concerning channel allocations and areas of priority. As with energy efficiency, these approaches all assume that a set of candidate locations is available.

3.1.3 Algorithmic planning summary

This discussion of algorithmic planning has described algorithmic planning and provided a typical example. A review of relevant literature established that algorithmic planning can solve sub-elements of the wireless network planning problem, particularly energy efficiency and coverage related problems. However, all of the literature reviewed assumed that a set of candidate locations was available and algorithmic planning suffers from the fact that the entirety of all the constraints need to be known up front and represented in an algorithmic way. Chapter 2 illustrated why having all of these constraints up front is so difficult. This indicates that the best approach may be computer-assisted planning where algorithmic planning can be used for specific problem sub-elements.

Requirement 4: a planning tool should support the option of using algorithmic planning for specific problem sub-elements.

3.2 Computer-assisted planning

A computer-assisted planning (CAP) tool assists the user in planning a wireless network by providing functionality and analysis conducive to wireless network planning. Functionality and analysis typical of a CAP tool includes the ability to create and name sites, set and adjust antenna heights, and conduct both point-to-point and point-to-multipoint analysis.

As pointed out in Chapter 2, the search space for wireless network planning is large, and with the inclusion of terrain, vegetation, access and placement information, the search space becomes difficult to deal with. The advantage of computer-assisted planning is that the problem can be approached by beginning with the basics. The user can then incrementally add information as necessary and this is much more suitable for community network planning.

The rural community may know that they want fast Internet access however all other inputs are vague to begin with. This makes the problem much more like a shopping exercise rather than an engineering exercise. The rural community may be willing to adjust certain features of the network and make trade offs to achieve different goals. For example, the community may accept a network plan with a maximum speed of 11 Mbps for half the price of a network plan with a maximum speed of 54 Mbps. On the other hand, the community may wish to spend a bit more by placing two relay sites to avoid placing a site at a location of cultural importance.

3.2.1 Evaluation of existing CAP tools

There are many commercial and freely-available CAP software solutions that are comprehensive and can produce viable network designs; however these tools are only suitable for the wireless network planning professional because the interfaces are designed for expert users. These interfaces expect the user to understand many of the complexities of wireless network planning and operation, and typically require detailed training in order to use the software.

It is difficult to fully evaluate CAP tools as trial versions of the commercial software are not readily available. Advertising material has been used to determine the capability of each piece of software and how they compare.

The following discussion explores how each of these tools assists in wireless network planning to determine how appropriate each tool is for the rural wireless network planning problem. The results of this comparison can help to identify what is required for a CAP tool that can be used by non-experts from a rural community.

Twelve existing tools were evaluated. Tools will be referenced by name and allocated letter in the following discussion. This is not an exhaustive list of tools but these twelve were found to be prominent tools for wireless network planning. Four research prototypes were considered for evaluation. Two prototypes, B-Hive [108] and ICEPT [121], are tools for planning urban cellular networks with a focus on optimal base station placement to provide coverage to areas with demand for mobile communication services.

The other two prototypes were indoor wireless network design tools. McGibney et. al [75] designed a tool for optimal placement of access points for indoor wireless communication systems and Guinard et. al [77] designed a tool for deploying building management systems relying on wireless sensors and actuators. All four of these prototypes are designed to provide wireless coverage to an area using algorithmic planning and then present coverage visualisations. The four prototypes are not present in the following discussion because at the time of investigation, the prototypes were limited in terms of a user interface and the only features that the prototypes supported were coverage analysis and height optimisation. Essentially, the prototypes were at an early stage of development and at that point were not in a position to contribute to the tool evaluation.

A Aircom International Connect [1] is a commercial CAP tool, screen shots indicate that it is for Windows.

B Mentum Planet [9] is a commercial CAP tool for Windows.

C ComSiteDesign [2] is a commercial CAP tool for Windows.

D The command-line Digital Line-of-Sight CAP tool for DOS 2.0 that is detailed in a report released by the US Department of Commerce in 1989 [68]. Though designed for "persons having no experience in programming", the program was intended for use by wireless system engineers. The Digital Line-of-Sight tool will be referred to as the DLOS tool in the following discussion.

E EDX SignalPro [4] is a commercial CAP tool, screen shots indicate that it is for Windows.

F Forsk Atoll [6] is a commercial CAP tool for Windows.

G Google Earth [8] is a virtual globe program for Windows, Linux and Mac that allows the user to explore the earth in a 3D environment. Though not actually a CAP tool, Google Earth is popular for wireless network planning as it is freely available and has useful features including: terrain elevation, satellite imagery, 3D visualisation, distance measuring tools, image overlay and elevation profile between two points.

H Overture Online [14] is a commercial CAP tool for Windows.

I Radio Mobile [18] is a Freeware CAP tool for Windows.

J Pathloss [15] is a commercial CAP tool for Windows.

K SPLAT! [20] is an Open Source CAP tool for Linux/Unix.

L WiTech [25] is a commercial Web-based CAP tool.

The twelve tools were compared based on their technical capabilities and support for local knowledge, geographic assistance, analysis features and user action support.. The author found these criteria most relevant for evaluating the planning tools based on earlier findings in Chapter 2. A planning tool should incorporate local knowledge and support the user throughout the planning process. It is important that technical criteria are met and that the planning tool supports features that allow the user to carry out the tasks and actions introduced in Chapter 2

The relative importance of some of the criteria such as optimisation support and data layers is not as important because these criteria enhance the planning capability but are not fundamental for the planning process. Other evaluation criteria exists could have been used for tool evaluation including: tool cost, source code license, hardware requirements and current users of the tool. However, the aim of this evaluation was to identify the capabilities of CAP tools. Other criteria would not assist in this aim and would possibly restrict the tools that were evaluated.

The frequencies supported by these tools are extensive. Radio Mobile (I) and SPLAT! (K) both support frequencies between 20 MHz and 20 GHz, due to their use of the Longley-Rice propagation model (discussed in Section B.5). EDX SignalPro (E) supports 30 MHz to 60 GHz while Pathloss (J) supports 30 MHz to 100 GHz. ComSiteDesign (C) supports 40 MHz to 40 GHz and Aircom International Connect (A) supports 300 MHz to 30 GHz.

DLOS (D) supports 1 GHz to 10 GHz while the other evaluated tools did not explicitly state their supported frequencies. With the exception of DLOS (D), Google Earth (G), Radio Mobile (I), Pathloss (J), SPLAT! (K) and WiTech (L), evaluated tools supported a large range of communication technologies. The majority of these technologies are cellular standards.

Existing tools were evaluated in four ways. The details of these evaluations can be found in Appendix A. Firstly, the tools were examined to determine whether they incorporate local knowledge and how they support the user. Five tools incorporated some aspect of local knowledge support and six tools had features that assist the user during the planning process.

Several existing tools provided algorithmic support with the most popular algorithmic method being antenna height optimisation. Table 3.4 shows whether the tools incorporate local knowledge and user support, as well as which algorithmic methods are supported.

Tools	Local knowledge	User support	Algorithmic planning support			
			Automatic Height Optimisation	Layout Optimisation	Automatic Frequency Planning	Automatic Power Control
A				x	x	x
B		x	x	x	x	
C			x	x	x	
D	x	x	x			
E	x	x	x	x	x	x
F			x		x	x
G						
H	x	x	x	x	x	x
I				x		
J	x	x	x			
K	x	x	x			
L						

Table 3.4: Feature support for existing tools including local knowledge, user support and algorithmic planning

Table 3.5 shows the results of evaluating the tools based on geographic assistance features. Google Earth (G) is the most featured tool in terms of geographic support. The entire earth is mapped using satellite imagery and aerial photography over 3D terrain and provides a wealth of geographic data layers such as transport, towns/cities and country/state borders.

Layers such as 3D buildings and key geographic features are also available for particular areas in the world, particularly the United States. Overture Online (H) is similarly featured but restricted to 2D maps with 3D visualisations.

Tools	Geographic support					
	Database support	3D visualisation	GIS integration	Map scale	Map orientation	Pan and zoom
A	x		x			x
B	x	x	x			x
C	x	x	x	x		x
D						
E	x	x	x	x		x
F	x		x	x		x
G	x	x	x	x	x	x
H	x	x	x	x	x	x
I	x		x			
J	x	x	x			x
K			x			
L						

Table 3.5: Supported geographic features for existing CAP tools

Table 3.6 shows the results of evaluated the tools based on analysis features. Path profile analysis and coverage analysis are fundamental to wireless network planning. Nine tools support path profile analysis. Google Earth (G) is capable of providing an elevation profile while WiTech (L) and Overture Online (H) did not currently have support for path profile analysis.

Ten tools support coverage analysis; DLOS (D) and Google Earth (G) were the two tools that did not support coverage analysis. Google Earth (G) can however display image overlays meaning that a coverage plot generated by another tool can be displayed in Google Earth.

Tools	Analysis support					
	Path profile	Coverage	Traffic	Interference	Capacity	Reliability
A	x	x	x	x	x	x
B	x	x	x	x	x	x
C	x	x	x	x	x	x
D	x					x
E	x	x	x	x	x	x
F	x	x	x	x	x	x
G						
H		x		x		
I	x	x		x		x
J	x	x		x		x
K	x	x				x
L		x			x	

Table 3.6: Supported analysis methods for existing CAP tools

Five actions were compared among six tools. These actions were the creation of a site, naming of a site, setting/adjusting antenna heights, conducting a point-to-point analysis and conducting a point-to-multipoint analysis. The six tools were DLOS (D), Google Earth (G), Overture Online (H), Pathloss (J), Radio Mobile (I) and Splat! (K). These actions were then compared against the criteria of being simple and straight-forward to carry out for non-experts from rural communities.

Table 3.7 shows the support for each of these five actions by the six tools. A detailed analysis of these actions is presented in Appendix A.4. This analysis identified Overture Online (H) as the most appropriate tool but unfortunately Overture Online does not implement the point-to-point analysis action which is fundamental for wireless network planning in rural areas.

Tools	Network planning actions				
	Creating a site	Naming a site	Selecting heights	Point-to-point analysis	Point-to-multipoint analysis
D	x	x	x	x	
G	x	x	x		
H	x	x	x		x
I	x	x	x	x	x
J	x	x	x	x	x
K	x	x	x	x	x

Table 3.7: Wireless network planning action support

3.3 Chapter findings

Although algorithmic planning is an excellent approach for sub-elements of the wireless network planning problem, it suffers from the fact that the entirety of all the constraints need to be known up front and represented in an algorithmic way indicating that computer-assisted planning is the better approach. A review of existing tools revealed that little support is present for incorporating local knowledge required to address the number of constraints in wireless network planning. Support for providing guidance while planning a wireless network is also inadequate for non-experts from rural communities. Evaluation found that Overture Online was the most appropriate tool for action support but did not implement point-to-point analysis. All of the tools evaluated, except Google Earth (G), are designed for expert users. As such, the terminology and types of available features are intimidating for the novice user. Commercial tools require significant training in order to use the tools effectively.

Radio Mobile (I) and SPLAT! (K) are designed for expert users. Radio Mobile (I) is intended for amateur radio operators and is used to predict radio system performance for an existing wireless network design. SPLAT! (K) is more suited to wireless network planning but as a command-line tool it expects all the technical parameters to be specified, hence is currently inappropriate for novice users. Google Earth (G) lacks general network planning support and therefore is also inappropriate.

Code reusability was considered when evaluating these tools. SPLAT! (K) was the only tool that offered code reusability as the other tools were closed source. SPLAT! (K) contained many useful functions for calculating link profiles and determining line-of-sight. Unfortunately at the time of investigation, the code for SPLAT! (K) was not well documented and difficult to follow.

Given that none of the evaluated tools were appropriate for use by non-experts from rural communities, it is possible to identify a list of features that an appropriate wireless network planning tool should support. The remainder of this thesis examines the identified list of features in more detail and discusses the development of a prototype wireless network planning tool suitable for use by non-experts from rural communities.

A wireless network planning tool should incorporate local knowledge and, where required, solicit that local knowledge. For example, when placing a site, the tool should solicit local knowledge appropriate to access and placement. A wireless network tool should support the user as much as possible, guiding them through decisions and helping the user with the process.

There are many optimisation methods that are potentially useful for wireless network planning as they assist in improving the wireless network plan. Regarding wireless network planning for rural areas, the most useful optimisation methods would be antenna height optimisation, automatic frequency planning and automatic power control.

There are several computer assistance features that can be part of a wireless network planning tool. Geographic features include multiple map types such as shaded terrain and aerial photos, GIS data such as a terrain database for extracting elevations and navigation aides such as scale, and orientation and the ability to pan and zoom. Analysis features include path profile and coverage analysis which are integral analysis tools in wireless network planning. Other forms of analysis that are useful include traffic loading, interference, capacity and reliability. Though useful forms of analysis, the latter four are not necessary for wireless network planning in low-density rural areas.

Tools should support all of the five actions for wireless network planning (creation of a site, naming of a site, setting/adjusting antenna heights, conducting a point-to-point analysis and conducting a point-to-multipoint analysis) and their implementation should be simple and straight-forward.

3.4 Chapter summary

The chapter has discussed algorithmic planning and presented a review of algorithmic planning literature. This review found that algorithmic planning was not suitable for the wireless network planning problem due to the broadness of constraints but worked well for sub-elements of the problem. The chapter then discussed computer-assisted planning and presented a review of relevant literature. The literature review revealed a list of features that a wireless network planning tool should support.

The key conclusion of this chapter is that:

- **a new planning tool is required to address the problem statement of this thesis.**

A requirement established in this chapter was that:

- a planning tool should support the option of using algorithmic planning for specific problem sub-elements (Requirement 4).

The next two chapters address the issues of the information required for wireless network planning and discusses potential computer assistance methods for use in a wireless network planning tool.

Chapter 4

Gathering information for planning a wireless network

This chapter investigates the findings of Chapter 3 further by describing the information necessary for planning a wireless network and how that information can be solicited from maps and local knowledge in the community. The chapter begins by presenting a methodology for identifying information that needs to be gathered. The chapter then presents an overview of the general local knowledge required and discusses the types of people in the community that may be able to contribute local knowledge. Finally, the chapter gives a detailed explanation of factors in the natural environment and the human environment that affect wireless network planning and how those factors can be identified using maps and local knowledge.

4.1 Methodology for information identification

In general, technologists have difficulty in envisioning the problems faced, unless they have visited the place, have been exposed to the conditions, and interacted with the people. Obtaining this local knowledge from the community can supersede information gathered from other sources, such as maps. The following section defines a methodology for identifying and gathering this information by considering the following questions:

4.1.1 Who was the first point of contact?

The CRCnet group was the first point of contact. Correspondence with the wireless network planning expert and associates took place. The author then met key members of rural communities that were involved in the deployment and maintenance of their respective rural wireless network.

4.1.2 What were the processes employed to gather the information?

Firstly the required information needed to be identified. This was done by:

- visiting rural wireless network installations to:
  - observe the physical surroundings to identify natural factors.
  - conduct informal conversations with community members to help identify human factors.
- consulting with the CRCnet group about previous experiences and problems.
- consulting relevant literature such as ITU radio propagation standards.

The information could then be gathered by:

- contacting companies such as local councils for useful data such as:
  - topographical maps, aerial photography and terrain data.
  - weather statistics.
  - locations of significant cultural sites.
- conducting further informal conversations with rural community members.

Throughout the process, cultural laws need to be noted so as not to antagonize and alienate the community – which would be detrimental to a project.

Although the author was familiar with Māori customs, two Māori experts were consulted and relevant literature examined. The CRCnet group had practical experience with Māori customs and so these experiences were also drawn upon.

4.2 Local knowledge

Communities are a rich source of local knowledge that can contribute valuable information for planning a wireless network. Local knowledge can be used to bring existing information up to date or to identify information that was not previously known. Knowledge of where trees may have been planted or existing trees removed can have a significant effect on where sites might be placed. Consulting with the local community can also encourage commitment of the future use of an area. A land owner may be willing to remove trees so that a link could pass through that area, or decide to plant trees else where so that the link can be established.

Consulting with the community to obtain information also supports the soft nature of the constraints, allowing features to be added, removed or modified where necessary. The budget for a network can change as people express interest in obtaining an Internet connection. Consulting with the community assists with determining who wants a connection to the network and therefore identifying the physical houses to be connected. People can share knowledge of high buildings with mains power in the area and who owns them. Members of the community including farmers, hunters, hikers and cultural experts can share information about the surrounding terrain and vegetation.

Local knowledge is best obtained by either by talking directly to members of the rural community, or prompting the rural community members for local knowledge using an intermediate component such as a computer program or questionnaire. Obtaining local knowledge can result in issues such as incomplete and inconsistent/conflicting information. Where these issues arise, it would be best to assume that the 'worst case' version of the information is correct, as this is more likely to result in a feasible network plan. One of the local community members should be responsible for making this call. A simple example would be where two community members disagree over whether a particular location is a burial ground or not. On the side of caution, the 'worst case' would be that the location is a burial ground. Where the resolution is not clear, the location or area for which the information is in question should be removed from current consideration until other possibilities have been discussed.

The task of detecting the 'worst case' version of information is currently carried out by the rural community members. The difficulty of detecting this 'worse case' is that most information will be a textual or verbal representation of local knowledge from community members. Detecting the 'worst case' would require the important elements of that information to be identified and contrasted with identified elements obtained from other community members. An expert system or similar could be used to record information from each community member. The system could ask specific categorised questions that have a fixed set of answers that could then be analysed by the system to determine the 'worst case'.

Information obtained during the planning process should not be discarded. It should be stored for future reference, particularly in case the wireless expert has questions during the network design verification stage. Information that is conflicting or incomplete should be noted and ideally resolved at a later time, again this may be during the network design verification stage.

Long term volatility can be regarded as positive or negative for the wireless network being planned. It is important for community members to try and consider all possibilities, and the likelihood of those possibilities occurring. For example, it is unlikely that a house would be removed and probably doesn't need to be considered as volatile, whereas trees are very likely to continue to grow and potentially cause problems in the future. Land use change over time could potentially create problems and possibly solve problems. For example, moving land usage from planted forest to dairying could solve radio propagation issues, whereas moving land usage dairying to planted forest could create radio propagation issues. This is another opportunity where an expert system or similar could ask about these long term volatility issues. In most cases where the network already existed, these changes would occur around the network in use.

Realistic costing of wireless deployments is an issue as costs change over time. The distributing ISP should provide current prices that have an expiry date. Users should clearly be informed when these prices have expired and should be given the opportunity to request updated prices. The overall cost of a network plan would not be guaranteed until reviewed by a wireless planning expert.

Requirement 5: a planning tool should allow local knowledge information to be entered and stored for future reference.

The following sections further identify these important aspects of information within the natural and human environments, illustrating how they affect wireless network planning and how local knowledge assists in this identification.

4.3 The natural environment

There are many natural features in the network environment that need to considered when planning a wireless network. Three types of maps were identified as being useful for assisting with identification of natural features: topographical maps, aerial photography and terrain maps. There may however be other types of maps that were not considered that could also be useful for assisting with identification of natural features. Terrain maps often use hill shading and a hypsometric colour scheme to produce a 3D-like visualisation of the terrain. Terrain maps typically show hydrological features such as coastlines, lakes, rivers and streams.

Terrain is the most obvious natural feature of which there are many forms. Hills, mountains, valleys and plains all have a different effect on wireless network planning. Slope, structure and composition of the terrain can be important in various situations. For example, hills and mountains can obstruct radio wave propagation, but a wireless site placed near the summit will potentially have significant coverage. Local knowledge of high spots overlooking large areas of land is useful when planning a wireless network.

It is often difficult to gauge terrain using an aerial photograph however a topographic map shows features such as contours, spot heights, depressions and cliffs. Often topographic maps are cluttered and can be difficult to interpret by inexperienced map users. Terrain maps aim to make terrain identification easier by presenting a 3D-like visualisation of the terrain.

Hydrological features such as rivers, streams, lakes, swamps, wetlands and the coast also need to be considered. Water is a barrier for placement and accessibility in most cases. A site will not be placed over water unless the site is designed for aquatic use or there is a stable platform above the surface of the water. Knowledge of where bridges and other types of crossings are located is necessary as crossing rivers and streams may be required to access sites. Water can also cause undesired reflection of the wireless signals at particular antenna angles. Terrain map typically show coastlines, rivers, streams and lakes. These features can also be identified in aerial photographs and topographic maps, as well as features such as swamps.

Vegetation such as single trees, bushes or entire forests have a significant effect on radio wave propagation. Placement of sites is limited somewhat by trees and in scrubby areas it may be necessary to trim or remove vegetation to place a site. Vegetation causes significant attenuation of radio waves as well as scattering the waves in all directions. Though these effects can be modeled, vegetation can be avoided by either transmitting around the area of vegetation or having the sites high enough to transmit over it, such as on hilltops or high buildings. Aerial maps are useful for locating vegetation but identifying the type of vegetation may be difficult due to the birds eye point of view. Topographic maps split vegetation in to categories including native forest, exotic forest, scrub, shelter-belts and mangroves. However, once again local knowledge is important as maps easily get out of date. New vegetation may have been planted, existing vegetation grown higher or even have been removed.

Protection of sites from animals, particularly on farms, is important to prevent possible damage to equipment. Cattle, possums and goats can chew wires and cause havoc with site equipment. It is best to have the site fenced off and/or high enough above the ground to deter most animals. Local knowledge can be used to determine the risk of damage from animals, and possibly the proximity to vegetation.

Local knowledge supersedes maps as local knowledge is generally current and considers features that are too small or outside the scope of features printed on maps. For example, features such as gorges, sink holes and small stands of trees may not be represented on a map or identifiable on an aerial photograph.

Requirement 6: a planning tool should support the use of maps for assisting with natural feature identification and local knowledge solicitation.

4.3.1 Climate

The climate should also be considered for the network environment. In most cases, climate precautions are common sense, though particular areas may require further consideration. The National Institute of Water and Atmospheric Research (NIWA) provides climate station data for its 30 climate stations throughout New Zealand including wind, rain and solar exposure data [13].

Climate consideration can help decide on alternative sources of power, such as solar or wind power, when mains power is unavailable. Local knowledge and/or appropriate data for that area should be consulted when considering the use of alternative power sources.

In New Zealand, south and east-facing slopes have limited solar exposure. Vegetation can also block solar energy. All maps will be of some use when considering slopes and shading from hills. Potential shading from vegetation can be identified using aerial photographs and topographic maps. Minimum sunshine hour data can give a near-worst case scenario of how much solar energy can be expected at that location.

Wind direction, speed and frequency is important when considering wind as a power generation source and may influence the building design of a site. Indicators that the site experiences high winds include stunted tree/shrub growth and wind shaping of vegetation. Wind can also affect sites on the network. Loosely-secured antennas could potentially be blown out of alignment by strong winds hence breaking the network connection and possibly wires as well. Significantly strong wind could dislodge a poorly secured site or blow other objects into it.

It is important to have some knowledge about the amount, direction and intensity of rainfall that a site will experience. High winds may drive rain horizontally or even vertically, hence equipment in areas subject to both high wind and intensive rainfall should be sealed to a high standard. Frequencies below 10 GHz are rarely affected by rain, however very heavy rainfall can cause some signal loss and link planning should take this in to account.

Lightning is a big risk to wireless sites as a lightning strike has the potential to severely damage site equipment. Wireless sites should use lightning rods and be properly grounded where there is any risk of potential strikes. Equipment should also be rated to withstand extreme temperatures common in that environment.

Requirement 7: a planning tool should support the use of climate data for assisting in site placement.

4.4 The human environment

Transportation infrastructure, such as road and rail, provide accessibility to site locations though can prevent site placement. For example, placing a site on a road or railway would be difficult, though not impossible. Permission from the appropriate authority would be required, as well as requiring a safe method of installation. The site would need to be durable to handle the possibility of being driven over. High traffic volume can have an effect on line-of-sight and cause additional signal loss due to reflection and diffraction of the signal by the passing traffic. Wireless links that cross road and/or rail with high volumes of traffic should do so at a height such that the majority of the signal clears the traffic to avoid additional signal loss. Topographic maps identify transportation features including roads, tracks, tunnels, bridges, fords and railways; transportation features can also be identified using aerial photographs.

Utilities such as fences and power structures such as poles and pylons can affect line-of-sight but can also be useful as a height advantage for site placement. Obtaining permission to place a site on such utilities may require more effort and money than building a stand-alone site. Underground utilities can make it difficult to place a site as digging will be restricted. Topographic maps identify major utilities such as fences, pipelines, power-lines, telephone lines and gas lines, while fences and overhead lines can be identified on aerial photographs. Local knowledge is necessary as minor utilities such as private pipelines and power-lines may not be shown on topographic maps.

Buildings such as houses, barns and cowsheds can also significantly affect line-of-sight. Buildings can however be used to the planner's advantage as buildings commonly have mains power and are of significant height. Topographic maps identify most buildings including residential areas, large buildings, isolated buildings, homesteads, churches, airfield/meteorological masts, towers and wind turbines. Most buildings can also be identified from aerial photographs. However, local knowledge is required to identify who the building belongs to and to obtain details of its construction. Identifying the owner is important as the owner's permission will be required and they may want compensation in the form of rent. Building construction information helps determine the ease of installing the site and how difficult wiring may be.

Wireless network sites can be a target for thieves as sites contain expensive equipment and substantial amounts of metal. Equipment should be encased in secure enclosures and security screws should be used. Sites should be fenced off for protection from vandals in areas where vandalism could be a problem. Risk to a site can be determined by considering the proximity of the site to roads shown on topographic maps and aerial photographs, accompanied with local knowledge.

Particular areas can be designated as forbidden zones for the wireless network. Often these areas are culturally sensitive sites such as historic battle grounds and cemeteries. In New Zealand, the Māori people regard prominent mountain summits as sacred and hence these sacred mountains should be respected. Some of these areas are present on topographic maps though many require identification by local experts. These areas typically forbid the placement of sites but transmission of radio waves is generally not a problem. In cases where transmission of radio waves through the area is a problem, this is usually due to potential legal or health issues.

Observatories and high-security facilities often have a radio-silence buffer zone requiring that there be no radio wave transmission in that area. Interference needs to be avoided when licensed frequencies are operating in the area. There is conflicting literature about the health effects of radio waves and some people refuse to have radio waves on their land or near their home. Legal requirements should be obeyed and other forbidden zones should be respected if not to keep the peace. Local knowledge plays an important role here, as this information would not be present on a standard topographic map.

Safety is an important issue that should be taken seriously. Though safety is more relevant during the building of network, it is useful to consider safety implications when deciding on a site location. High structures should be fenced off to avoid unauthorized people such as local children climbing and injuring themselves. Workers should use appropriate climbing gear on high structures. Care should be taken to ensure that there are no sharp edges on the structure and equipment should be securely mounted. A site may be located near a cliff or other hazardous terrain. Common sense and local knowledge can be used to ensure safety.

Accessibility to sites must be strongly considered during the planning process. Site structures may require timber, steel and concrete to build which are heavy and difficult to transport. Once the network is up and running, sites need to be quick to access in case of site failure. Batteries for solar sites are large and heavy, while antennas can also be large and awkward to carry. Site locations should be accessible by 4WD and where this is not possible, walking distance should be minimised. A helicopter may be required to deliver heavy equipment for remote sites. Aerial photography, topographic maps and terrain maps can all be used to determine accessibility to sites. Again, local knowledge is important as it incorporates many details that maps do not, such as how winter access compares to summer access.

Proximity to mains power should be strongly considered when site locations are chosen. Often this means that wireless sites will be constructed on the roof of a building such as a house so wiring to mains power is simple. In other cases where the wireless site is close enough, power can be trenched or a cable run overhead from mains power nearby. In rural environments however, sites will often be located far away from any source of mains power. In these instances, sites require an alternative power source such as solar or wind, and large batteries to store the charge. These types of sites incur more cost but offer line-of-sight and coverage benefits due to their location. For example, a solar site on a high mountain may reach four distant sites, whereas otherwise extra sites would be required. Topographic maps and aerial photography can help find sources of mains power by showing building locations. Local knowledge is required to verify the availability of mains as a building shown on the map may not have mains power.

Requirement 8: a planning tool should support the use of maps for assisting with the identification of features in the human environment that may impact on wireless network planning and soliciting associated local knowledge.

4.5 Chapter summary

This chapter has presented a methodology for identifying information to be gathered and has given an overview of the general local knowledge required for wireless network planning. The chapter described the implications of natural features, the climate and factors in the human environment, in terms of their effect on wireless network planning.

The following requirements for a planning tool were identified:

- a planning tool should allow local knowledge information to be entered and stored for future reference (Requirement 5).
- a planning tool should support the use of maps for assisting with natural feature identification and local knowledge solicitation (Requirement 6).
- a planning tool should support the use of climate data for assisting in site placement (Requirement 7).
- a planning tool should support the use of maps for assisting with the identification of features in the human environment that may impact on wireless network planning and soliciting associated local knowledge (Requirement 8).

Chapter 5

Link feasibility analysis

This chapter addresses the key issue of determining the feasibility of a link in wireless network planning. The primary factor required to determine the feasibility of any link, point-to-point or point-to-multipoint, is to estimate the degree of loss that the link will experience. An important indication of this loss is line-of-sight—if there is no line-of-sight, then most wireless technologies will not be able to establish a functioning link.

Wireless line-of-sight is a technical constraint in wireless network planning and is different than visual line-of-sight. As radio waves propagate, they also spread out the further they travel. This phenomena is modeled using an ellipsoidal volume of space known as the Fresnel zone (Figure 5.1). A link profile plot is a visual method used to show both site endpoints, the curvature of the earth, the terrain and the direct path. The innermost Fresnel zone is considered the most important for link feasibility analysis. The size of the Fresnel zone is wavelength dependent because the wavelength determines the maximum radius/width of the ellipsoid.

The significance of the innermost Fresnel zone is that it defines the terrain clearance required to achieve wireless line-of-sight. Any obstacles, such as trees, buildings and mountains that obstruct the innermost Fresnel zone, will have an impact on radio wave propagation. Minor obstruction of the innermost

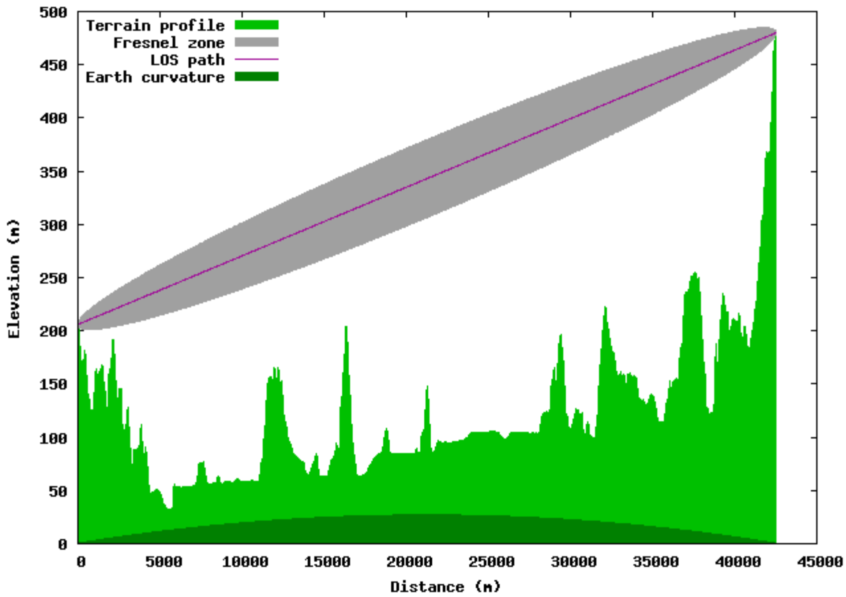


Figure 5.1: Example of a link profile plot showing the terrain, line-of-sight and the innermost Fresnel zone.

Fresnel zone can be tolerated but is generally recommended by propagation experts to be less than 40% of the Fresnel radius at the point of obstruction [45]. Radio wave propagation theory is covered in more detail in Appendix G.

Determining wireless line-of-sight is the first step to determining whether a given link is feasible. The frequency of a link is a technical constraint where there is a trade-off between the capacity of the link and the ability of the link to deal with minor obstructions. Radio waves at lower frequencies travel further, and are better at traveling through and around objects, however, radio waves with higher frequencies can transport more data [70]. The distance of a link is constrained by terrain and frequency. To determine the influence of technical constraints such as link distance and frequency, it is necessary to use a radio wave propagation model to predict the loss that the link will experience.

5.1 Chosen propagation models

The details of the propagation models considered for link feasibility analysis are discussed in Appendix B. Each of the propagation models described in Sections B.2, B.3, B.4 and B.5 were considered based on how that particular model is applicable to rural wireless network planning. Rural New Zealand is the focus of this thesis and so key characteristics of rural New Zealand have been used to evaluate which propagation models are most suitable. The primary issue in rural New Zealand that affects radio wave propagation is terrain. The terrain of rural New Zealand is considered irregular—irregular terrain can be described as terrain that varies in elevation significantly over short distances. The radio wave propagation model findings in this section would be relevant to other rural environments that also have irregular terrain.

Models such as the Free Space Path Loss model and the Friis model are inappropriate for link prediction in areas of irregular terrain due to their requirement of free-space—the space that the link exists in contains no particles and no fields of force. Any predictions by a model requiring free space would likely yield inaccurate results as free-space does not consider the affect of terrain on radio wave propagation.

The plane-earth two-ray reflection model assumes short distance links and ignores the curvature of the earth assuming relatively flat terrain. There are links in a rural wireless network of length where the curvature of the earth is important and the two-ray model does not consider the curvature of the earth. The two-ray model assumes that the terrain is flat and smooth, which is not true for terrain in rural New Zealand. Link predictions in rural New Zealand using the two-ray model are likely to be inaccurate because of this terrain assumption.

Vegetation models are useful when there is vegetation data to analyse. WiPlan does not currently support vegetation data though this is a desired feature for future work. The ability to predict loss due to vegetation would increase the confidence in whether a given link was feasible. In this future work, WiPlan would most likely implement the ITU vegetation model due to the models ability to predict loss in different vegetation situations.

Urban models ignore the terrain between the transmitter and receiver as the model assumes that the transmitter would normally be located on hills. Additionally, the Hata model is restricted to links of less than 20 kilometres in length. As a result, propagation prediction would be inaccurate and many links would be considered line-of-sight when in fact they are obstructed by terrain. Predictions of links greater than 20 kilometres in length using the Hata model would also be inaccurate.

The Egli model assumes gently rolling terrain with average hill heights of approximately 15 metres and is valid for frequencies between 40 MHz and 1 GHz. The lowest commonly used frequency for wireless network technology is 2.4 GHz which is well outside of this range. Some areas of New Zealand have gently rolling terrain that fit this model but the frequency limitation would lead to inaccurate predictions.

This leaves the irregular terrain model and the ITU terrain model for consideration. Both models support a large range of frequencies from 20 MHz to 20 GHz as well as a wide variety of distances and antenna heights. However, the irregular terrain model does not produce valid predictions for paths under one kilometre in length and the ITU terrain model only considers the highest point in the terrain. Links from a relay to houses can be less than 1 km and so it was decided to incorporate both models. The irregular terrain model is used for links exceeding one kilometre in length and for shorter links the ITU terrain model is used. Other models were not applicable for paths under one kilometre because the other models do not consider the affects of terrain obstructing a link. It is now possible to create tools for determining connectivity and line-of-sight using the irregular terrain model and the ITU terrain model.

5.2 The link profile and area profile tools

The *link profile tool* is used to establish line-of-sight connectivity when the user creates a link by estimating the path loss and creating the data necessary to obtain a link profile plot. The *link profile tool* was implemented using the C programming language. The tool is designed to work with plane coordinate projections, such that coordinates can be described in terms of distance north or south and east or west from the projection's point of origin. Distance north or south is commonly referred to as the northing and distance east or west as the easting. The projection used for implementing and testing the *path profile tool* is the New Zealand Traverse Mercator (NZTM) projection [12]. Any other projections, such as WGS84, should first be converted to a linear projection. A 3-tuple description is required for the two sites at each end of the path being profiled: easting, northing and height above terrain. A frequency and polarity also need to be specified. A digital elevation model in the same projection as the site coordinates is required that covers the necessary area.

The *link profile tool* is reliant on the Geospatial Data Abstraction Library (GDAL) [7] for dealing with the digital elevation models. Digital elevation models are represented as rasters and contain meta data for geo-referencing purposes. Such meta data includes the origin and pixel size. The origin is the geographic coordinate in the chosen projection for a corner pixel, typically the top-left. The origin is in turn a coordinate based on the projection's point of origin. Pixel size reflects the resolution of the digital elevation model. As an example, the 500 meter digital elevation model of New Zealand has an origin for the top-left pixel with an easting of 1488800 meters and a northing of 6239495 meters. The pixel size is stored for both axes in case they are different, for this example both axes are 500 meters in size.

Elevation extraction must be done in terms of pixels and hence using the above meta data, GDAL can determine a relationship between the projection coordinate system and pixel coordinate system. The coordinates for the sites involved can be translated to their pixel counterparts once the relationship is known. Elevations along the path are then extracted by interpolating along the path between the two sites.

Once elevation has been extracted for the entire path, one of two propagation models is used to predict line-of-sight and associated loss, depending on the distance between the two sites. The Irregular Terrain Model [83] is the preferred choice however it is limited by being invalid on distances less than 1km. In these cases, the ITU model [33] is used to predict propagation loss based on most significant terrain obstruction, using only the point of obstruction and operating frequency.

The *area profile tool* is used to create a coverage plot and is based on the *link profile tool*. The *area profile tool* creates a coverage plot by performing link profile calculations between the selected location for computing coverage and every point in the coverage area. A configuration file can be supplied in order to have more fine grained control over the coverage being calculated. Configuration options include bounding box selection, antenna specification and confidence settings; a full example configuration file is included in Appendix H. The focus of WiPlan so far has been on using point-to-point links and as a result, there is currently no integration of the configuration file in the user interface of WiPlan. Further integration of the configuration file within WiPlan as part of future work would provide more flexibility for coverage prediction including custom distance ranges and coverage segments.

Both of these tools are invoked by the external applications controller (described in Section 7.1) in WiPlan. When the user is creating a link, the external applications controller runs the *link profile tool* for every mouse movement event that WiPlan receives. A lower resolution digital elevation model is used in this case to ensure that the process finishes in near-real time. When the user has finished creating the link, then the external applications controller runs the *link profile tool* with a higher resolution digital elevation model which takes a few seconds. The results of this is then shown in the *link profile information window*. The *area profile tool* is invoked by the external applications controller when the user creates a coverage plot. At this stage, the configuration for the coverage is fixed, however it is intended that interface functionality for coverage configuration would be added to WiPlan in the future.

5.3 Decision tree

A simple decision tree was designed and implemented by the author to diagnose the results of the link profile tool in order to give a meaningful report to the user - that is, whether or not the wireless link will function appropriately. This decision tree was developed by considering the main problems faced when establishing a physical wireless link in consultation with experts from the CRCnet group. There are three main problems to solve: whether the link is line-of-sight, whether the link will be legal and whether there is a suitable antenna.

In WiPlan, the problem of line-of-sight is split in two: WiPlan can determine line-of-sight in terms of land formation but cannot determine line-of-sight with respect to other objects such as buildings and trees. The decision tree therefore considers four questions and there are associated non-technical explanations for each possible result of traversing the decision tree. The non-technical explanations were derived by the author with some refinements suggested during early prototyping. These explanations could be refined further as part of future work, based on feedback from showing the explanations to members of rural communities. Figure 5.2 shows the four key questions that this decision tree is composed of.

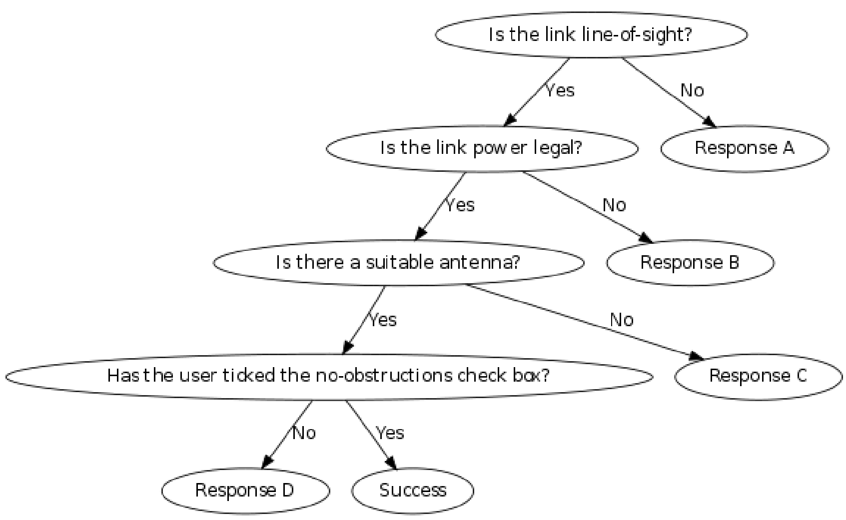


Figure 5.2: The decision tree used in WiPlan for diagnosing a link.

When a link is created, the link analysis determines whether the link is line-of-sight and predicts the loss incurred by the link. As part of this analysis, a link budget is used for each viable frequency to calculate important factors (link budget is described in Appendix G.7). For each viable frequency, a wireless interface can also be determined. Using a link budget with the predicted loss allows the required antenna gain to be calculated. The decision tree can now be used to establish the feasibility of the link, given that line-of-sight has been determined and the required antenna gain has been calculated.

The first step of the decision tree is to determine whether the link is line-of-sight and by how much the first Fresnel zone is obstructed, if at all. In the case where the link is not line-of-sight, the user is prompted with Response A: "The link is obstructed by terrain, try raising the heights at either or both ends of the link using the buttons below otherwise consider creating a new link".

When the link does have line-of-sight, the second step of the decision tree is to determine if the link is legal with respect to power regulations. This is calculated using the predicted loss to determine the what antenna gain would be required to achieve the link. In turn, the EIRP can be calculated and compared to the New Zealand power regulations. When EIRP is in excess of the regulations, the user is prompted with Response B: "The legal power limits are exceeded, try introducing a relay site otherwise consider creating a new link".

The third step of the decision tree is to find an antenna that meets the required gain calculated previously. The higher the gain of an antenna, typically the more expensive that antenna may be, and hence some distributing ISPs may not supply an antenna with sufficient gain. When no antenna exists in the list with sufficient gain, the user is prompted with Response C: "There is no antenna with sufficient gain to sustain this link, try introducing a relay site otherwise consider creating a new link". Another solution for an advanced user would be to manually add a high-gain antenna to WiPlan using the *antenna* *configuration tool.*

The final step of the decision tree is to check that the user has ticked the no-obstructions check box in the *link profile information window.* This is to ensure that the user has checked the area for obstructions or has sufficient local knowledge to verify that there are no obstructions that may interfere with the link. When the user has forgotten to tick the check box, they are reminded with Response D: "Check that there are no obstructions that might block the link such as buildings or trees and tick the check box in the *link profile information window*". In the case where the check box is ticked, the chosen protocol and cost are presented to the user. The protocol of lowest cost is chosen where there is a choice between 802.11a and 802.11b (most often this will be 802.11b). The user can however change the protocol based on knowledge of interference in the area.

5.4 Chapter summary

This chapter has discussed the key issue of link feasibility analysis in wireless network planning and described an approach for determining link feasibility. The importance of line-of-sight and the affect of distance and frequency were discussed. An evaluation of eleven documented radio wave propagation models established that the irregular terrain model and the ITU terrain model are the most suitable models for rural New Zealand due to their support of terrain, frequency and distance. The link profile tool and area profile tool were developed to use the irregular terrain model and the ITU terrain model to predict connectivity and coverage respectfully. Finally, a decision tree was developed that used the loss and line-of-sight predictions from the link profile tool with a link budget to present the user with a non-technical explanation of whether the link is feasible.

Chapter 6

The process of designing the WiPlan user interface

This chapter discusses the design process followed for developing WiPlan. Firstly, methodology overview for designing the interface is discussed. The design requirements identified earlier in the thesis are summarised and some new requirements are defined. The stakeholders and actors involved in the wireless network planning process are then introduced, followed by a description of five rural personas based on characteristics of typical rural people. The chapter describes an overview of the WiPlan user interface as well as identified use cases and how those use cases were implemented in the WiPlan interface. Finally, the WiPlan system is subjected to the same analysis as the existing planning tools described in Section 3.2.1.

6.1 Methodology overview

This section gives an overview of the methodology used to design the WiPlan interface. The spiral model [50], developed by Barry Boehm, was chosen as it uses iterative development which allows for incremental refinement to the user interface. The spiral model forces early user involvement in the system development and allows for new requirements to be addressed as they become known.

The four stages of the spiral model are:

1. Determine the objectives of the design.

2. Identify and resolve the risks involved.

3. Develop and test.

4. Plan the next design.

A simplified version of the spiral model is used for designing the WiPlan interface that incorporates three stages: design, implement and evaluate. Figure 6.1 shows the simplified spiral model.

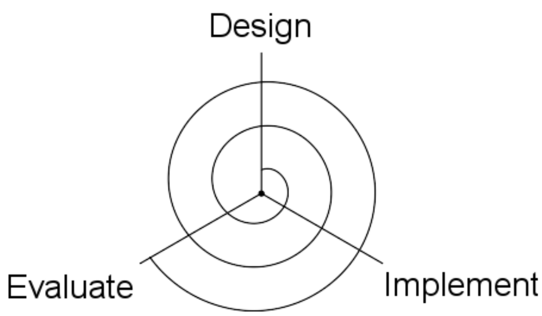


Figure 6.1: The spiral model

The design stage is where the objectives and the constraints of the project are identified. This forms the base of the spiral model and is key to the entire interface design process. A major part of this stage is the identification of the requirements for the interface and the target users that will be using the interface. Section 6.1.1 summarises the requirements that have been identified for the WiPlan user interface throughout the earlier chapters of this thesis. Identifying target users and designing the user interface for these users is critical to the success of the interface design. Section 6.1.3 describes how the users were identified.

The implementation stage is where the actual interface development takes place, usually by using a prototyping approach. The evaluation stage is where the implemented prototype is evaluated and the feedback from that evaluation applied to the prototype in the next design phase. A prototype was developed and incrementally refined through eight re-design cycles around the spiral for the development of WiPlan. Design one was the intial paper prototype. The paper prototype was presented to an evaluation panel of three people (two HCI experts and a wired network expert who lives in a rural community) to give feedback on weak points in the interface design. The implementation of WiPlan then began to take place and is described in Chapter 7. Design two through to design five were the implemented results based on feedback about the previous design from the evaluation panel.

Design cycle six and design cycle seven were the implemented results from design five and design six respectively, based on extensive feedback given by two independent HCI experts. The findings of the two HCI experts is discussed in Chapter 8. Design eight is the implemented result of first user study discussed in Chapter 9 and is the final interface design of WiPlan. A second user study took place using this final design and user feedback is discussed in Chapter 9.

6.1.1 Interface design requirements

The requirements for the WiPlan user interface design can be derived from the thesis question: Can a software tool be designed to assist members of rural communities with no expertise in wireless network planning, to plan a feasible wireless network?

There are two observations that can be made from this question:

1. The interface needs to be designed for members of rural communities
2. The interface needs to support collaborative wireless network planning by non-expert users

By analysing these two observations in conjunction with the GNOME Human Interface Guidelines [49], the interface design requirements can be identified. The GNOME Guidelines were used as they are well documented, widely used and implementation of WiPlan took place in a GNOME environment.

The following functional requirements for a planning tool were identified in earlier chapters.

A planning tool should:

- Requirement 1: solicit information about potential constraints (Section 2.2).
- Requirement 2: support the use of any of the planning strategies identified in Section 2.3 (Section 2.3).
- Requirement 3: support all of the tasks and actions identified in Section 2.4 (Section 2.4).
- Requirement 4: support the option of using algorithmic planning for specific problem sub-elements (Section 3.1.3).
- Requirement 5: allow local knowledge information to be entered and stored for future reference (Section 4.2).
- Requirement 6: support the use of maps for assisting with natural feature identification and local knowledge solicitation (Section 4.3).
- Requirement 7: support the use of climate data for assisting in site placement (Section 4.3.1).
- Requirement 8: support the use of maps for assisting with the identification of features in the human environment that may impact on wireless network planning and soliciting associated local knowledge (Section 4.4).

Members of local rural communities are of various ages from different education backgrounds. It is anticipated that most community members involved in the network planning will be 'middle-aged' but in some cases teenagers and possibly children could be involved. The level of comfort and experience with computer use also tends to vary greatly amongst rural community members. As a result, the user interface needs to be suitable for users of various ages and computer experience. The number of user actions should be small, so that novice and first-time users can carry out simple tasks successfully, and thus reduce anxiety, build confidence and gain positive reinforcement [114].

The interface design needs to minimise the number of user actions and the memory load on the users as it is expected that WiPlan will only be used once by a particular group of users and therefore those users will be first-time users. Shneiderman et al. states that in geographic applications, it seems natural to give a spatial representation in the form of a map that provides a familiar model of reality.

Shneiderman et al. also points out that the success of a spatial data-management system depends on the skill of the designers in choosing icons, graphical representations, and data layouts that are natural and comprehensible to users. Therefore it seems sensible to provide a map-based interface using direct manipulation, as direct manipulation interaction allows users to carry out tasks rapidly and observe the results immediately. This is appealing for novices as it enables easy learning, retention and encourages exploration.

Two important functional requirements for the interface design can be derived from the preceding discussion:

- *Requirement 9:* The interface should be map-based and should provide direct manipulation interaction.

- *Requirement 10:* The interface should support the wireless network planning process, incorporating the tasks, actions and strategies defined by Requirement 2 and Requirement 3.

The following non-functional interface design requirements are derived from the preceding discussion and the GNOME Human Interface Guidelines [49]:

- *Requirement* 11: Understand the users, and understand both their goals and the tasks necessary to achieve those goals (GNOME guideline 1.1).
- *Requirement* 12: The vocabulary used should be restricted to a small number of familar, consistently-used terms (GNOME guideline 1.3)
- *Requirement 13:* The interface design should follow common conventions as used in Windows operating systems. For example, left-clicking the mouse should allow the user to select interface objects such as buttons (GNOME guideline 1.4).
- *Requirement 14:* The user should always be aware of what is happening as the application should be provide appropriate feedback as required (GNOME guideline 1.5).
- *Requirement 15:* The interface design should be simple and intuitive to avoid user confusion (GNOME guideline 1.6).

These requirements were consulted throughout the interface design process whenever a design decision needed to be made. Each design decision was evaluated against each of these requirements and adjusted where necessary to meet these requirements.

6.1.2 Stakeholders

Szabó et. al [118] points out that the stakeholders of community networks include:

- public agencies
- users
- private sector service providers
- local and global facilitating agencies.

In the WiPlan rural wireless network planning scenario, these stakeholders are identified as the following:

- public agencies
- the local rural community
- the developers of WiPlan
- the distributing ISP

6.1.3 Actors

The distributing ISP and the local rural community are the two key stakeholders that need to be considered in the WiPlan interface design. These groups were explored further by informal consultation with the CRCnet group and observation by participation. The author had constant access to the CRCnet wireless network planning expert and the senior network engineer. They were available on demand as questions arose and were informally interviewed many times, primarily about how the group worked as an ISP. The expert and engineer were also able to provide information about community users they had met.

An invaluable method for understanding characteristics of rural communities was observation by participation. The author visited the Te Pahu network, introduced in Section 1.2.1.1, several times. Visits included accessing a solar site on a farm, visiting a school and visiting some houses. On these occasions, the author visually observed the surrounding environment and the people that were met.

The author also visited the Tūhoe network, introduced in Section 1.2.1.1, spending three days with local iwi community members and members of the CRCnet group. During this visit, the author met two community champions that lead and encouraged the community to utilise the wireless network. The author also met several community supporters of various ages, two in their late teens. The author visited and actively participated in wireless installations at a farmer's wool-shed, a school and a house in the community. The author climbed a sacred mountain with the CRCnet expert and some of the community supporters to carry out some solar site maintenance. Two other solar sites were visited during this time. One of the community supporters was also the local network installer and was informally interviewed about their role. These visits gave a valuable insight to real rural community members and greatly assisted identifying the target end users.

Based on these experiences and observations, six actors can be identified that belong to the distributing ISP and the local rural community groups. It is important to note that an end user can belong to more than one actor type.

The wireless network expert (distributing ISP)

The wireless network expert is a wireless network planning professional. There is generally only one wireless network expert involved but sometimes there may be more. The wireless network expert has minor involvement in the planning process until near the end when verification of the network plan is required.

The primary goals for the wireless network expert are:

1. Profit by getting rural communities on board.

2. Assist rural communities with quality wireless network design and verification.

The wireless network helpdesk or installer (distributing ISP)

The wireless network helpdesk are the part of the distributing ISP that the rural communities tend to deal with face-to-face. In some cases, there may be no wireless network helpdesk and instead the wireless network expert will also play this acting role. The wireless network helpdesk has the same goals as the wireless network expert.

The community champion (community)

The community champion is the typical trigger for the rural community wireless network planning process. The community champion is the person (or persons) that motivate the community to plan the wireless network and get the distributing ISP on-board in the first place. The primary goals for the community champion are:

1. Build a community wireless network.

2. Bring the community together.

3. Obtain access to the Internet.

The local knowledge contributor (community)

The local knowledge contributor is a member of the local community that contributes local knowledge information as part of the planning process. Generally there will be several local knowledge contributors taking part. The primary goals for the local knowledge contributor are:

1. Identify and share relevant local knowledge for wireless network planning.

2. Obtain access to the Internet.

The computer operator (community)

This actor is required for the WiPlan planning process. The computer operator is a member of the local community that is comfortable operating the computer running WiPlan. Members of the community may take turns at playing this role. The primary goals of the computer operator are:

1. Operate WiPlan and plan a wireless network with other community members.

2. Obtain access to the Internet.

Community interested party (community)

The community interested party are the members of the community that want access to the Internet but do not want to participate in the network planning process. Their primary goal is:

1. Obtain access to the Internet.

Actors can be categorised as being a community member or an ISP member. The primary actor in the rural wireless network planning process is the community member, as they share the common goal of wanting access to the Internet and they are willing to work together towards that goal. The next section describes the personas that were developed for the community member actor based on the experiences and observations discussed earlier.

6.1.4 Personas

A persona is a description of a stereotypical user that is used by interface developers to guide the design of the user interface and the interactions that take place. Personas help to guide the design of the user interface by providing a focus and fostering development of empathy towards the personas by the designers. Personas also force the designers to think about specific use cases and how that persona might cope in that situation. A persona includes personal information such as age, sex, family, job and hobbies, as well as the real-world needs and goals of that stereotypical user. The more specific the personas are, the more effective they are as design tools [59]. Table 6.1 presents the set of characteristics that encompass the end users. These characteristics can then be used to help establish personas.

Characteristic	Target end-users
Age	Will range in age from teenagers to 80+
Gender	Both male and female
Ethnicity	All, primarily NZ European and Māori
Education	May have only minimal education qualifications
Occupation	Primarily agriculture, education or small business
General computer experience	May have little or no prior experience with using computers
Spatial reasoning	Likely to be quite skilled with distances and heights
Domain experience	Expected to have no prior experience with wireless network planning
Attitude	Positive and eager to work towards a community wireless network

Table 6.1: Characteristics of target end-users.

Five personas have been established to represent some of the real-world rural people who would be expected to use the WiPlan interface. These personas were chosen as they are based on real people that the the CRCnet group has liaised with. The personas were identified through consultation with the CRCnet group and by meeting key rural community members that have an active role in the management/maintenance of their respective rural wireless network.

These five personas are intended to be representative by encompassing a set of varying viewpoints on the local areas. The five personas include: a sheep and beef farmer, a dairy farmer, a school principal, a community representative and a cultural expert. The details of these personas are available in Appendix D. An analysis of Internet use in New Zealand by Statistics New Zealand [39] was used to help create these personas, details of which can be found in Appendix.

Two of the five established personas are based on farmers. In terms of area, sheep and beef farming and dairy farming are two of the dominant farm types in New Zealand in terms of land area. The two personas therefore reflect the stereotypical character of the sheep and beef farmer, and the dairy farmer.

The persona of a principal of a local rural school was chosen to represent the importance of education among rural children and highlight the importance of the Internet for learning in a modern society.

The community representative is an important persona as that persona is responsible for conveying the thoughts and issues of people in the community.

The final persona is the cultural expert, or a representative of the cultural expert. The cultural expert is responsible for maintaining the fine balance between cultural respect and planning a wireless network that meets expectations of the other personas. The cultural expert will typically be a person from that culture. For example, in Māori culture, the expert would be a kaumātua[1], or a representative of the kaumātua.

[1]Kaumātua are respected elders who are the keepers of the knowledge and traditions of the family, sub-tribe or tribe [48].

6.2 WiPlan user interface overview

This section presents a description of the main components of the WiPlan user interface including the WiPlan tutorial and guide, the main interface and the advanced tools.

6.2.1 The WiPlan tutorial and guide

WiPlan includes a tutorial that introduces the user to each of the main tasks within WiPlan and steps the user through completing each of those tasks. The tools embedded within WiPlan are also introduced such as map zooming and panning. The WiPlan tutorial provides a structured step-by-step work flow of the tasks to be completed through direct manipulation of the user interface and teaches the user the planning process (Requirement 10). As well as creating a pre-determined wireless network plan, the tutorial provides general learning so that the user gains familiarity with how to perform wireless network planning tasks in WiPlan.

The tutorial has been integrated in to the main interface instead of using approaches such as popups to keep the interface simple. This prevents the tutorial being accidentally hidden behind other dialogs where users may not be able to find it. As the user completes the step-by-step instructions, the tutorial will automatically advance to the next step. The tutorial introduces the user to such tasks as: creating sites, creating links, solving line-of-sight issues, exploring areas and creating coverage plots. The full tutorial is presented in Appendix F.

WiPlan also includes a guide for assisting the user in the wireless network planning process. WiPlan shows the guide when not in tutorial mode and provides support for when the user is unsure about what they should do next. The guide provides five steps that describe the reverse-branch strategy discussed in Section 2.3.4. The reverse-branch strategy was chosen as it is the strategy used by the CRCnet researchers. The guide is optional and WiPlan supports the use of any of the strategies described in Section 2.3.

6.2.2 The main interface

Figure 6.2 shows the main interface of WiPlan which consists of a tool bar (A & E), side bar (B & C), main map window (as per Requirement 9) and a status bar (D, I & J). The tool bar shows four buttons for changing the mouse mode on the main map window (A). The first, from left to right (A), is the simple select-type mode, followed by the zoom in, zoom out and pan modes. The toolbar also contains a drop-down list (E) that allows the user to switch between a terrain map, topographic map and aerial photography. The side bar contains a legend for explaining features on the map (C) and a tutorial that steps the user through the actions required when planning a wireless network (B). The status bar below the main map window shows the user the current geographic location and elevation of the mouse pointer (D). The status bar also shows the current connectivity of the network plan (I) and the total cost (J).

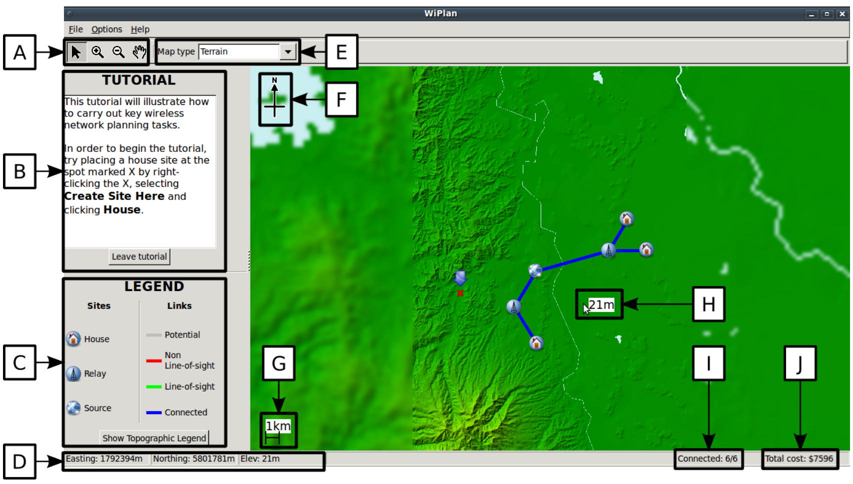


Figure 6.2: The main screen of WiPlan.

The compass rose (F) and scale (G) on the map window assist the user with map navigation. The compass rose provides the user with orientation and follows the common convention that north is at the top of the map. North on the compass rose is aligned to true/geographic. The scale gives the user a feeling for the size of features on the map. It also allows the user to gauge approximate distances. A small helper text box follows the mouse cursor (H) around the map window showing the elevation at the mouse cursors location so the user does not have to move their eyes from the cursor in order to see the elevation. Every persona is not necessarily expected to understand the map portion of the main interface but as the planning is collaborative, it is reasonable to assume that at least one of the users is familiar with maps. For example, farmers use maps for day-to-day farming tasks, such as moving stock from one paddock to another. Figure 6.3 shows an example of how the the name and type of a site are displayed when the mouse cursor hovers over a site. Figure 6.4 shows an example of how the cost of a link is displayed (if applicable) when the mouse cursor hovers over a link. A cost is not shown when the link is non line-of-sight, as an equipment solution cannot be determined without line-of-sight. The file menu supports typical features such as open and save, as well as advanced tool options and a help about option.

Figure 6.3: An example of the mouse helper text box when hovered over a site.

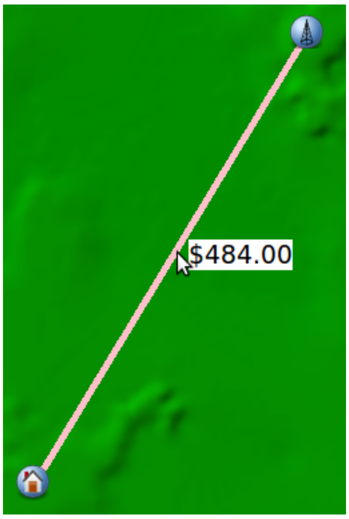


Figure 6.4: An example of the mouse helper text box when hovered over a link.

6.2.3 Advanced tools

There are two advanced tools included with WiPlan; the *interface configuration tool* and the *antenna configuration tool*. The *interface configuration tool* and *antenna configuration tool* are, as the names suggest, for the configuration of interfaces and antennas respectively. The configuration tools are intended for the distributing ISP and expert users; most users should not need to use them. On the other hand, the *site adder tool* is for entering the coordinates of known sites, and therefore will most likely receive significant usage.

Figure 6.5 shows the *interface configuration tool.* At the top of the tool window there is a button for adding new interface configurations. These configurations are specified in XML files and clicking the button will display an open file dialog. Added configurations will then be displayed in a tree-like structure in the interface configuration tool. Each interface type forms the root of the sub-tree representing that interface configuration. An interface configuration can be removed by right-clicking the interface type and selecting delete item. The OK button at the bottom of the window saves any changes made.

Figure 6.6 shows the *antenna configuration dialog* which has two main parts; the current configuration and existing configurations. The current con-

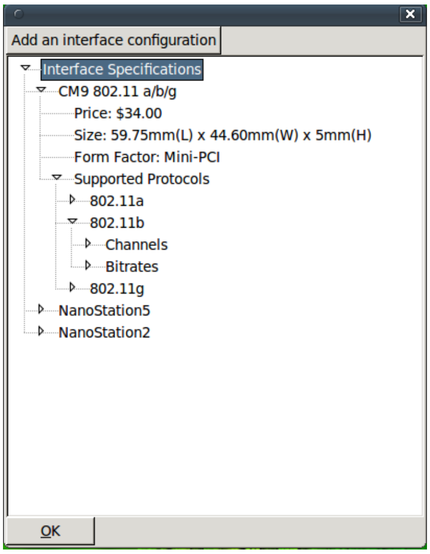


Figure 6.5: The interface configuration tool in WiPlan.

figuration allows the addition of a new antenna or the modification/removal of an existing antenna configuration. The current configuration shows such information as the antenna name, type, gain, azimuth, elevation, supported frequencies and price. Each of information elements can be modified or the entire configuration removed. The existing configurations table shows all previous defined antenna configurations and the selected configuration is shown in the current configuration. When a blank row in the table is selected, as is the default, then a new antenna specification will be added. Existing antenna configurations can be loaded from appropriate CSV files or saved to CSV files.

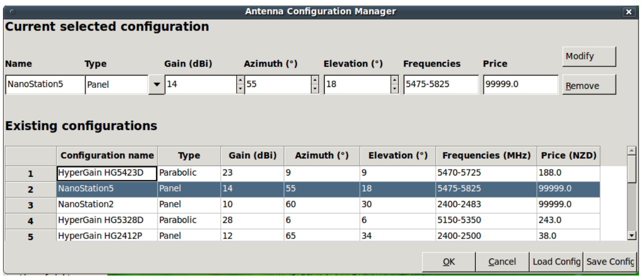


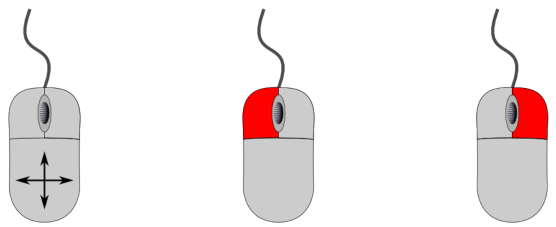
Figure 6.6: The antenna configuration tool in WiPlan.

6.3 Use cases and implemented functionality

The following section describes the use cases derived from **Requirement 3**: that a planning tool should support all of the tasks and actions identified in Section 2.4. The derived use cases are:

1. Finding a site location.
2. Creating a site.
3. Accessing site properties.
4. Creating a link.
5. Computing line-of-sight.
6. Computing coverage analysis.

Figure 6.7 shows the icons and their associated meaning for explaining some of the interactions that take place.



(a) Move the mouse. (b) Left-click. (c) Right-click.

Figure 6.7: Icons representing mouse operations.

6.3.1 Finding a site location

Use Case 1 Finding a site location
Primary Actor: Computer Operator
Scope: Subsystem
Level: User Goal
The computer operator wants to decide where they should create a site. The operator may be trying to find a particular site, such as a house, or deciding where to place a relay site.

Finding the location for a site depends on whether the site to be placed is a source, house or relay site. Locations for source sites should already be provided with WiPlan by the distributing ISP. Section 6.3.1.1 explains how the computer operator might find a particular house location in order to create a site there. Section 6.3.1.2 explains the issues that need to be considered by the computer operator when deciding where to place a relay site.

6.3.1.1 Finding houses

There are three main techniques to finding houses in WiPlan. The first technique is to use the advanced *site adder tool* if coordinates are known for the houses. The second technique is to use satellite imagery to locate the approximate area and use roads and other features to locate houses using local knowledge. Both of these techniques will yield fairly accurate coordinate locations. The third technique is to use topographic maps to locate houses by identifying roads and other features using local knowledge. Depending on the age of the house and the quality of the topographic map, individual houses may or may not be present on the map. When the house is not present on the map, bends in roads and rivers and features such as vegetation will be necessary to estimate the location of a house using local knowledge. In this situation, it is important to remember that the accuracy of placement may be questionable and nearby terrain and vegetation should be considered closely.

6.3.1.2 Choosing relays

A relay is chosen by considering five key issues: elevation, placement, access, power and weather. Creating a relay at an elevation higher than most of the surrounding area assists with establishing line-of-sight links and increases coverage possibilities. Permission for placing a relay needs to be obtained from the landowner and other parties, such as local iwi. Access to the site, power requirements and weather conditions at that site also need to be considered. Potential relay sites are usually identified using maps and local knowledge. A user may already know of elevated locations where a relay may be suitable and search for those areas using topographic maps. Otherwise the user can look for elevated locations using the topographic map or the terrain map. The topographic map shows contours and trig sites, while ridges and peaks can be identified by the shading on the terrain map. Coordinates can also be entered using the advanced *site adder tool*. Most relay locations are chosen based solely on elevation to begin with and then the issues of placement, access, power and weather are considered. A relay location can then be disregarded if any of these issues can not be sufficiently addressed.

6.3.2 Creating a site

Use Case 2 — Creating a site
Primary Actor: Computer Operator
Scope: Subsystem
Level: User Goal
The computer operator wants to create a site. The operator specifies the location of where they want the site created and the type of site they want it to be. The system then creates the correct type of site at the specified location.

A site can be created by moving the mouse to the desired location and right-clicking the map to show the pop-up menu with site creation options. Figure 6.8 shows the steps involved in creating a house site.

Alternatively, the *site adder tool* can be used to create sites. Figure 6.9(a) shows the *site adder tool* being used to create five sites. The result of creating these five sites can be observed in Figure 6.9(b). The current coordinates shows the current site to add, or the details of a site that has been added but not yet created. Sites listed in the table are not created until the user clicks OK. The user enters the site name, coordinates, coordinate type and site type. Currently, the supported coordinate types are the World Geodetic System (WGS84) used by GPS devices and the NZTM projection. Site coordinates can be imported from and exported to CSV files.

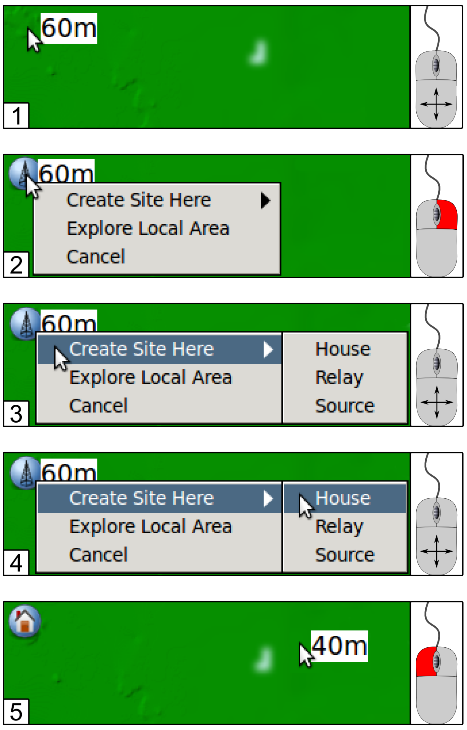
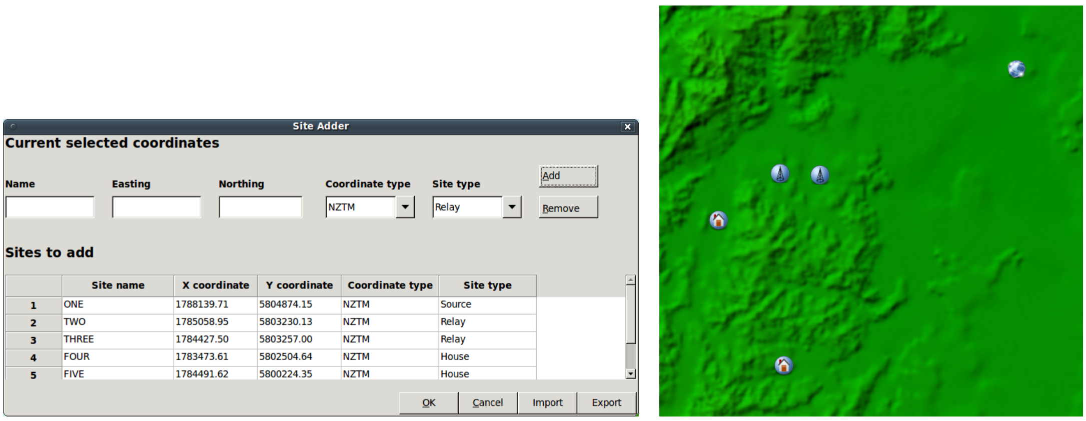


Figure 6.8: Creating a site



(a) Entering sites to add in the Site Adder.

(b) Sites created after the user clicks OK.

Figure 6.9:

6.3.3 Accessing site properties

Use Case 3 Accessing site properties
Primary Actor: Computer Operator
Scope: Subsystem
Level: User Goal
The computer operator accesses the site properties for a site. The computer operator can read and/or modify attributes for that site. When the computer operator is finished with the site properties, they can choose whether or not to save their changes.

Site options can be accessed by selecting and right-clicking a house to display the pop-up menu, as shown in Figure 6.10. Selecting *Site properties* will display the *site properties information window* for the selected site.

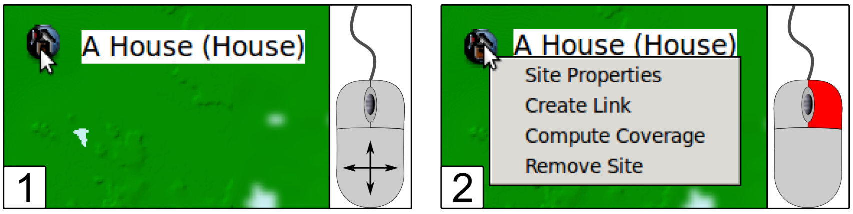


Figure 6.10: Accessing a menu

Accessing the site properties is slightly different depending on whether the site is a house/source site or a relay site. Section 6.3.3.1 explains the functionality of accessing site properties for a house/source site, while Section 6.3.3.2 explains the functionality for accessing site properties for relay site.

6.3.3.1 Site properties for a house/source site

Figure 6.11 shows the *site properties information window* for a house site. The same *site properties information window* is used for a source site. The *site properties information window* contains general information at the top of the window with some more specific information that will be described as encountered during the tutorial. The name of the house is shown in a text field which allows the user to specify the name of the house. The type, coordinates and elevation of the house are shown in label fields.

The user can select the approximate antenna height from the drop-down list where each height in the list has a brief description such as *One storey house (4m)*. The button next to the drop-down list activates a dialog that allows for a custom height and description to be added to the drop-down list. Users often do not know exact heights and so a description can be more meaningful than an actual number. Specification of an exact height may be off-putting to the user as they may worry about how specific the height measurement needs to be. The notes area is different depending on the type of the site. The general notes text field allows the user to store general information such as who owns the house or building in question.

The weather information section shows the estimated weather conditions for the site location; including sun, wind and rain. The estimated weather is presented using a five-star rating system as well as raw values. The five-star rating system is intended to convey a visual rating of the weather types, where five 'stars' indicates a very high level and one 'star' indicates a very low level. The 'star' levels were derived using New Zealand building regulation information and weather data. The about button provides access to a dialog explaining the source of the weather information. Another button accesses a dialog that allows the user to enter raw weather data.

6.3.3.2 Site properties for a relay site

Figure 6.12 shows the *site properties information window* for a relay site. The information window for a relay is similar to the dialog for a house. The drop-down list for the power source allows the user to select whether the relay site uses mains power or solar power. The cost and power requirements of the site

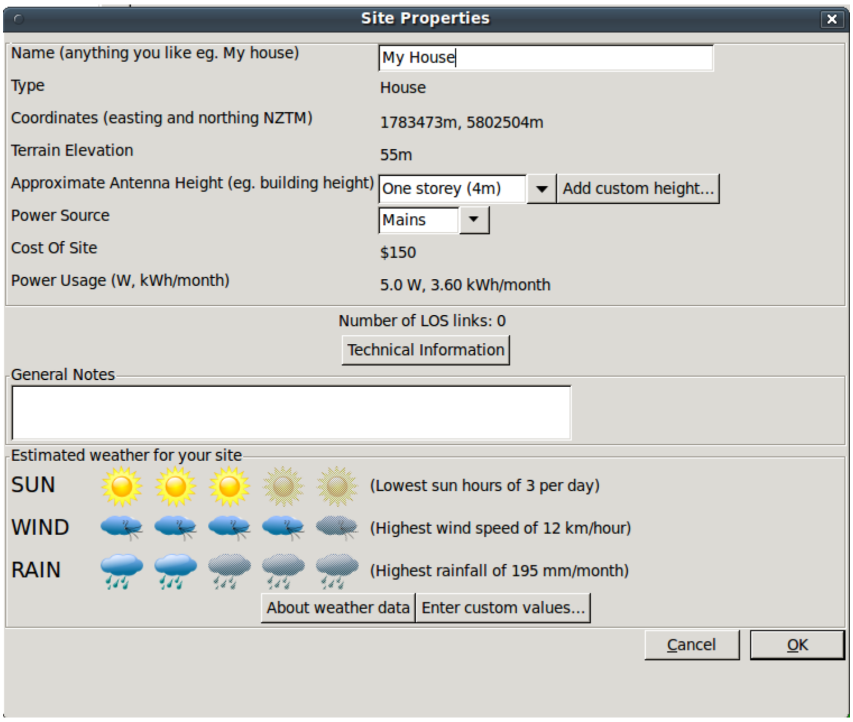


Figure 6.11: An example of the *site properties information window* for a house site.

are shown in label fields. However, the notes area for a relay site is significantly different to that for a house or source site.

The placement notes area contains a check box that should be checked by the user if permission to place the site at that location has been obtained. A multi-line text field allows notes specific to placement to be recorded. A button next to the text field displays a help dialog with some examples. For example, "the land owner gave permission to build the site however the summit is sacred to the local iwi. The local iwi were consulted and agreed that the site could be built 5m below the summit. The ground is rocky in places and may be difficult to dig".

The access notes area contains a drop-down list for selecting the dominant form of transport to the site. This is to encourage the users to consider access to the site. A multi-line text field allows notes specific to access to be recorded. A button next to the text field displays a help dialog with some examples. For example, the dominant transport type could be set to 4WD and the recorded notes could be "This site is located at the back of a farm on a high hill. A farm race gets most of the way there and then it is necessary to pass through two paddocks. In wet conditions, it would be better to walk through the two paddocks". The weather information section is the same for a relay site as for a house or source site.

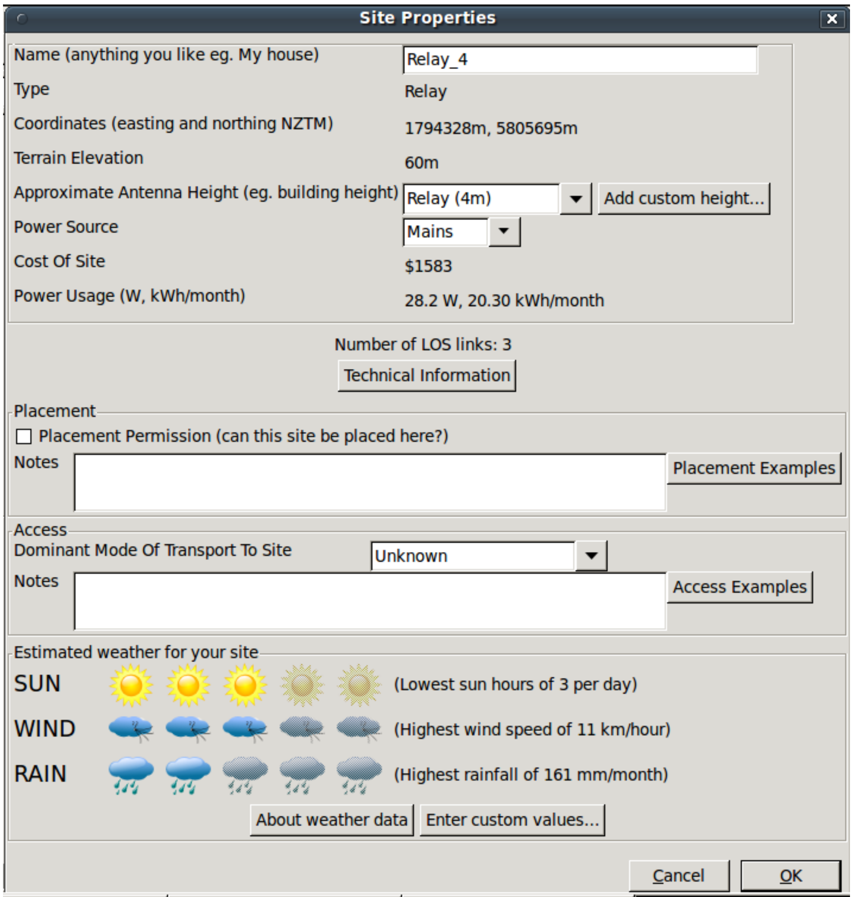


Figure 6.12: An example of the site properties dialog for a relay site.

6.3.4 Creating a link

Use Case 4 Creating a link
Primary Actor: Computer Operator
Scope: Subsystem
Level: User Goal
The computer operator enables link creation mode and creates a link between two sites. Once a link has been created, the system indicates to the computer operator whether the link is line-of-sight or not.

Selecting *Create link* from the site pop-up menu puts WiPlan in to link creation mode. When the user moves the mouse, a dashed red or green line, with the current site as its origin, will follow the mouse pointer (Figure 6.13). The green line indicates line-of-sight while red indicates no line of sight but neither are as precise as when a link is analysed in the *link profile information window*. This is because the indicator needs to be repeatedly calculated as the user moves the mouse and in order for the indicator to keep up with the user, lower resolution terrain data is used for the calculations. The *link profile information window* only needs to calculate line-of-sight once and can take a bit more time for the calculation, so much high resolution terrain data can be used.

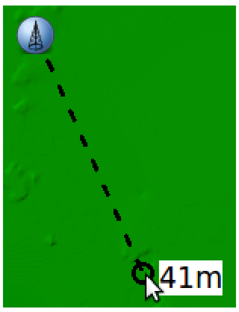


Figure 6.13: An example of the line-of-sight indicator in WiPlan.

When a link is created, WiPlan will show the *line-of-sight confirmation dialog* showing the protocol to use and the cost if there are no issues with line-of-sight (Figure 6.14). The dialog simply asks the user whether there are any obstructions such as trees or buildings that could block line-of-sight. If the user selects no then WiPlan creates the link. If the user selects yes, then WiPlan still creates the link but the link is classed as non line-of-sight.

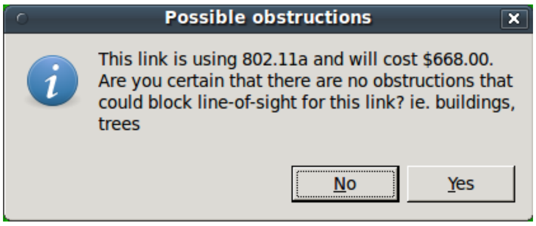


Figure 6.14: An example of the line-of-sight confirmation dialog in WiPlan.

A link can be removed by right-clicking the link to display the pop-up menu which shows two options; *Link profile* and *Remove link*. Selecting *Link profile* would open the *link profile information window*. The user should left-click *Remove link* which will remove the link and any configurations on the sites connected by the link, but will not remove the sites themselves.

6.3.5 Computing line-of-sight

Use Case 5 Computing line-of-sight
Primary Actor: Computer Operator
Scope: Subsystem
Level: User Goal
The computer operator has created a link between two sites and now would like to see if the link has line-of-sight. The computer operator would like to know if there is a problem with line-of-sight between the two sites and would like to obtain some assistance from the system to resolve the problem.

When the user creates a new link, or right-clicks on a link and selects *Link profile*, the *link profile information window* is displayed. There are three variations of the link profile; Figure 6.15 shows the successful *link profile information window* and Figure 6.16 shows the failed *link profile information window*. Figure 6.17 shows the third variation which occurs when user input is required for the link to be successful. Both information windows consist of five parts; link feedback, link information, link profile plot and antenna height adjustment.

The link feedback part consists of two label pairs and a symbol. The first label pair shows the protocol solution, or “None” if there is no solution. The symbol next to this depicts the link status. A red cross symbol shows the user that the link failed because there is no solution due to line-of-sight blockage (Figure 6.16). An orange ellipsis indicates to the user that their input is required (Figure 6.17). A green tick symbol shows success when there is a solution (Figure 6.15) . The second label pair presents the cost of a solution if there is one, otherwise shows the reason for failure and what the user can do for the link to be successful. The details of how the decision tree behind this process works is discussed in Section 5.3.

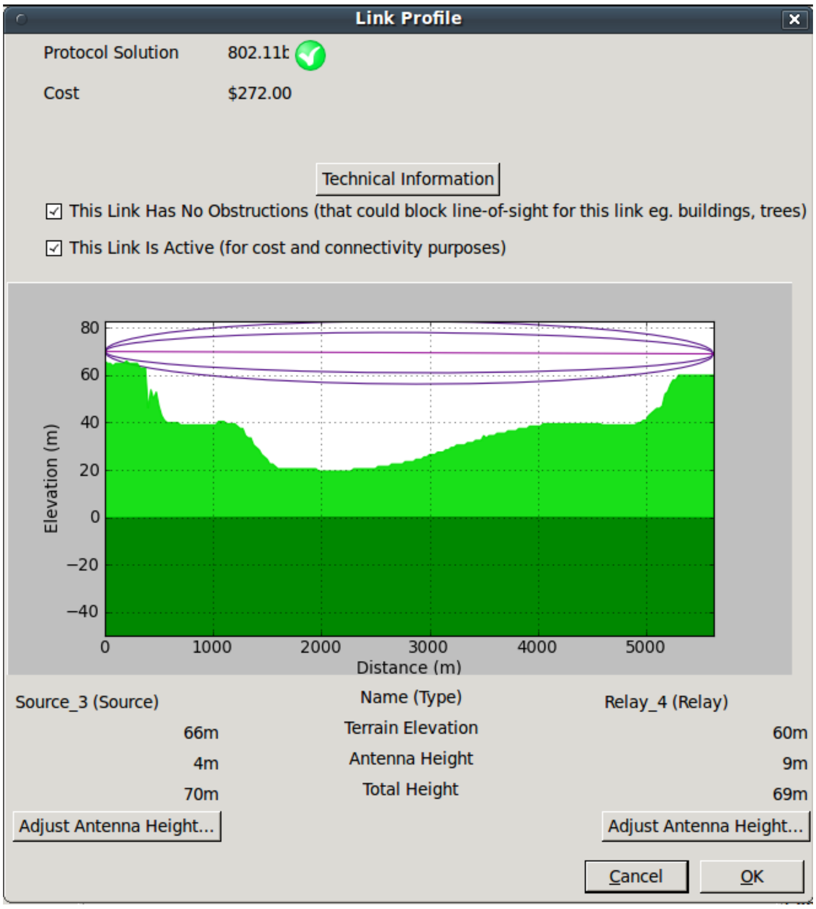


Figure 6.15: An example of the link profile information window where the link is successful.

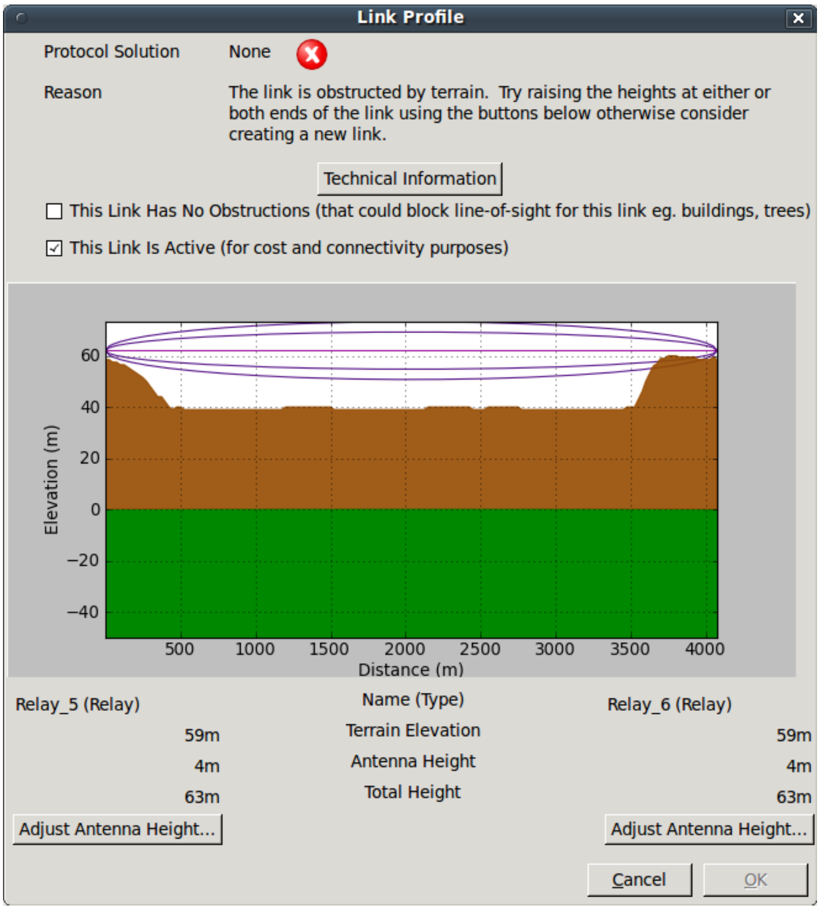


Figure 6.16: An example of a link profile dialog where the link has failed.

The link information part consists of three elements; a button and two check boxes. A button allows access to the technical information dialog describing the protocol results determined for that link. Results calculated for the link using 802.11a and 802.11b include whether the link is line-of-sight, whether the link is deemed legal, the frequency range, the radio card and antenna that should be used, and the cost. This information is intended for an expert and hence is in a separate dialog to avoid cluttering the link profile information window and confusing users. The first check box should be ticked by the user if the link has no obstructions such as trees or buildings that could block line-of-sight. This is the user input required to transition from the user input required state (Figure 6.17) to the successful state (Figure 6.15) and requires local knowledge to ensure that line-of-sight exists. The other check box allows the user to activate or deactivate a link for exploring variations of a network plan.

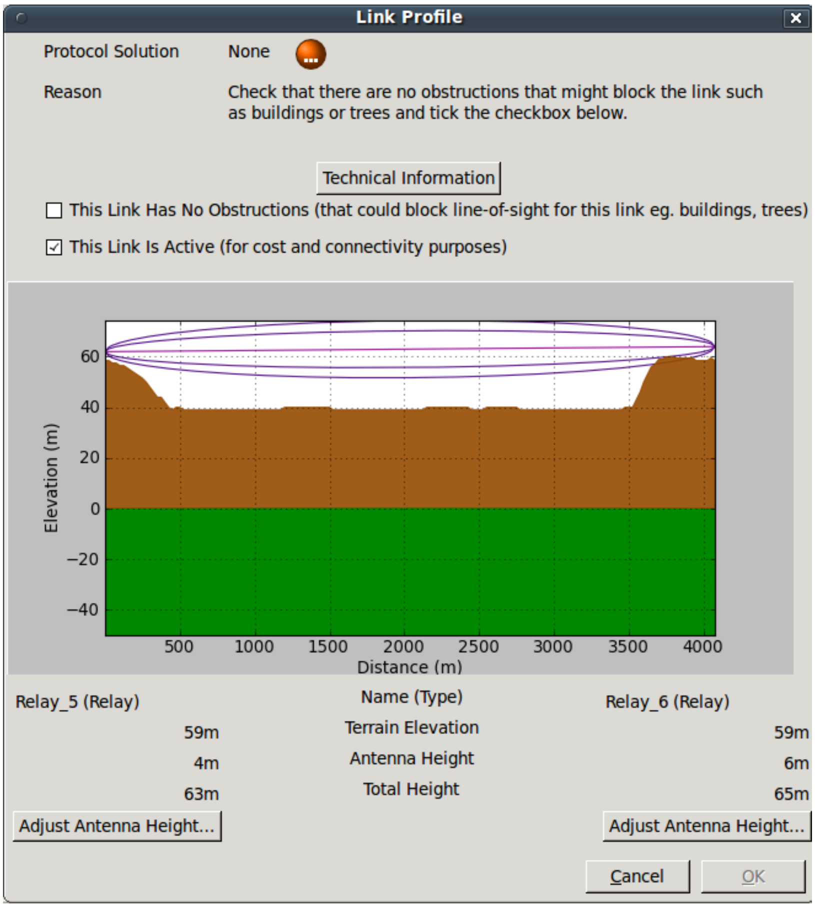


Figure 6.17: An example of a link profile dialog where user input is required.

The link profile plot shows a cross-section of the terrain between the two sites, showing the line-of-sight path and Fresnel zones for 802.11a and 802.11b. When a link does not have line-of-sight, the terrain in the link profile plot is a dull brown colour, otherwise the terrain is green.

The antenna height adjustment part shows the name and type for the left and right sites; such that name and type of the left site was left-aligned with the left edge of the link profile plot and the name and type of the right site was right-aligned with the right edge of the link profile plot. This makes the link profile information window more aesthetically pleasing and makes the association of the antenna information to the link profile plot easier to understand for the user. The terrain elevation and antenna height is shown for each site. The total antenna height is shown for each site so that the user could associate the total antenna height with the elevation read from the link profile plot; the total antenna height being the sum of the terrain elevation and the antenna height above ground. Each site has an associated button for adjusting the antenna height for that site. Clicking the button will show a dialog that allows the antenna height to be adjusted. Applying this antenna height adjustment will recompute line-of-sight for the link and the entire link profile information window will be updated to reflect the changes. For example, the height adjustment may transition the link from the failed state (Figure 6.16) to the user input required state (Figure 6.17).

6.3.6 Computing coverage analysis

Use Case 6 Computing coverage analysis
Primary Actor: Computer Operator
Scope: Subsystem
Level: User Goal
The computer operator would like to compute the coverage analysis for the site. Ideally they would like to specify a transmission distance and then be shown on the map where that site has coverage.

Compute coverage will create a coverage plot to a radius of two kilometres from the selected site and will display it on the map (Figure 6.18). The coverage plot shows all locations within two kilometers that have line-of-sight to the selected site. The focus of WiPlan so far has been on using point-to-point links and as a result, there is currently no user interface options for computing coverage (though this is intended as part of future work). A radius of two kilometres was chosen to help determine if a relay site can provide connectivity to houses nearby. Also, as the coverage radius increases, the coverage computation time also increases. Right-clicking the coverage plot gives the option to hide it.

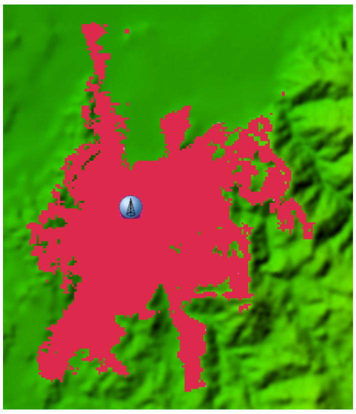


Figure 6.18: An example of a coverage plot created for a relay site in WiPlan.

6.4 Evaluation of WiPlan features

WiPlan has implemented many of the features discussed in Chapter 3. This section evaluates WiPlan based on the same set of features that the existing tools in Chapter 3 were evaluated against. These features include incorporating local knowledge, supporting the user during the planning process and supporting features that allow the user to carry out the tasks and actions introduced in Chapter 2.

6.4.1 Local knowledge and user support

WiPlan provides local knowledge and user support in several ways. The site properties information windows for house and source sites provide a notes text field for providing ownership details and other relevant information. Users are encouraged to think about placement issues such as whether they have permission to build a site at that location by a check box for confirming permission as well as a notes text field for additional notes in the site properties information window. They are also encouraged to think about how that site might be accessed by a drop-down list for selecting the dominant form of transport for accessing that site as well as a notes text field for additional notes in the site properties information window. The ability to select the power source enables users to use their knowledge of mains power supply in the area. The *line-of-sight confirmation dialog* asks that users consider whether there are any potential obstructions to line-of-sight such as trees and buildings using local knowledge.

The tutorial and guide also encourage the users to think about local knowledge as well as supporting the users through the wireless network planning process. The tutorial introduces them to the main features of WiPlan and some network planning tricks. The guide then provides support for what to do next when the users get stuck in the wireless network planning process.

6.4.2 Algorithmic planning support

Algorithmic planning support was not included in the current prototype of WiPlan. WiPlan currently supports the core functionality for rural wireless network planning - algorithmic planning support is not fundamental for rural wireless network planning. Algorithmic does however assist in the planning process and is therefore considered as part of future work for WiPlan .

Antenna height optimisation is used to determine the antenna heights at both ends of a link to ensure line-of-sight. This functionality is implemented within WiPlan but is not part of the interface as yet.

Access point layout optimisation determines the best locations for access points based on a set of demand locations. Though the WiPlan interface does not currently support access point layout optimisation, the area profile tool used for determining coverage in WiPlan (discussed in Section 5.2) can identify optimal access point locations based on demand locations.

Automatic frequency planning optimally assigns radio channels for all links in a network such that any interference is minimised. Automatic power control is used to optimally assign power levels to each transmitter to reduce interference while maximising signal quality. WiPlan implements automatic power control by automatically determining the necessary equipment required for a link to function.

6.4.3 Computer assistance

WiPlan provides several methods of geographic support and analysis support for wireless network planning.

6.4.3.1 Geographic support

WiPlan supports three map types including: a terrain map that shows elevation changes, peaks and ridge lines; a topographic map that shows roads, houses, contours and other information; and satellite imagery where available. WiPlan uses a terrain database as a source for obtaining elevation data, such as for site elevations and when computing line-of-sight for a link. The map area of WiPlan shows a compass rose for orientation and a scale for determining the size of map features. WiPlan provides three modes for map navigation: pointer mode for interacting with the map area, sites and links; zooming mode for zooming in and out of the map area; and panning mode which allows the map area to panned.

6.4.3.2 Analysis support

The main analysis assistance supported by WiPlan is link profile analysis and coverage analysis as these are fundamental to wireless network planning. The link profile analysis presents a link profile plot and information explaining whether the link is line-of-sight. The coverage analysis computes a coverage plot for a two kilometre distance around the site in question. Reliability analysis is provided on a per link basis by satisfying the link budget (discussed in Appendix G.7) when a link is established. WiPlan does not consider traffic types but configures links to use the highest bit rate that the selected protocol is capable of. WiPlan analyses links based on the highest bit rate available for each protocol and ensures reliability however WiPlan does not yet allow selection of lower bit rates. WiPlan does not provide support for interference, capacity or global reliability analysis. These analysis methods may however be added in the future.

6.4.4 Wireless network planning action support

WiPlan supports the five main actions necessary for wireless network planning. These actions are the creation of a site (A1), naming of a site (A2), setting/adjusting antenna heights (A3), conducting a point-to-point analysis (A4) and conducting a point-to-multipoint analysis (A5).

Creating a site (A1) A site can be created in WiPlan using either the *site adder tool* or manually by right-clicking on the map to show a pop-up menu. This menu shows two options: *Create site here* and *Explore local area.* Selecting *Create site here* then shows a list of the types of sites that can be created: a source, relay or house site.

Naming a site (A2) A site can be given a name in WiPlan by right-clicking the site to show the pop-up menu with four options: *Site properties*, *Create link*, *Compute coverage* and *Remove site.* By selecting *Site properties,* the site properties information window will be displayed for the site. The name for the site can then be entered in the name text field. Clicking OK will save the new name for the site.

Selecting heights (A3) WiPlan provides two methods for selecting heights: using the *site properties information window* or the *link profile information window* (discussed in the Point-to-point analysis section). The *site properties information window* can be accessed as for naming a site and the height for the antenna can be selected from the drop-down menu. It is also possible to enter a custom height.

Point-to-point analysis (A4) Point-to-point analysis is conducted when a non line-of-sight link is created or when a link is right-clicked and *Link profile* selected. The *link profile information window* is displayed showing a link profile plot and information regarding line-of-sight and antenna details. Either antenna height can be adjusted by clicking *Adjust antenna height* for the appropriate antenna and entering the new height.

Point-to-multipoint analysis (A5) Point-to-multipoint analysis is conducted when the menu for a site is accessed and *Create coverage* is selected. A coverage plot is created with a range of two kilometres that is then displayed on the map.

6.5 Chapter summary

In this chapter, the design process for developing WiPlan has been discussed. The design requirements for the WiPlan interface were identified as were the stakeholders and actors involved in the wireless network planning process. Five personas based on characteristics of typical rural people were introduced. The chapter then discussed the interface design and associated features of WiPlan in detail. The chapter concluded with a feature evaluation of WiPlan, subjecting WiPlan to the same evaluation method that the existing tools in Chapter 3 were subjected to. This evaluation showed that WiPlan supports the majority of features identified for general wireless network planning and all of the features deemed necessary for rural wireless network planning.

Chapter 7

Implementation

This chapter discusses the implementation details of WiPlan including the internal architecture of WiPlan and the libraries that were used. WiPlan was developed over a period of five years. The first two years were spent understanding the subject area and its multi-disciplinary nature, while also developing the link profile and area profile tools (discussed in Section 5.2). Another two years were spent on the interface design and implementation, with the final year consisting of the WiPlan evaluation and thesis write-up.

Existing tools made it difficult for algorithm reuse as most of the tools were closed source and those that were open-source were not well documented at the time of investigation. Therefore, aside from the functionality provided by software libraries, and the Irregular Terrain Model [83] mentioned in Chapter 5, all implementation is work of the author.

7.1 Development environment and WiPlan architecture

WiPlan was developed on the Ubuntu operating system for its ease of use for software development. Ubuntu is based on the Debian GNU/Linux distribution and distributed as free and open source software. The programming languages and associated libraries used in development of WiPlan are cross-platform, so WiPlan could potentially be compiled to run on operating systems other than Ubuntu, such as Microsoft Windows.

WiPlan was predominantly developed using the Python programming language [17]. Python is a powerful dynamic language that is fully modular and supports and extensive set of standard libraries. Python is available for all major operating systems and has an open source software license.

Three main software libraries (wxPython, GDAL and pubsub) were used to achieve the functionality in WiPlan. The wxPython library is a cross-platform GUI toolkit for Python that allows programmers to create robust graphical user interfaces [26]. The FloatCanvas [47] widget was perhaps the greatest contribution of wxPython to WiPlan. The FloatCanvas forms the map of the main interface in WiPlan. FloatCanvas provides a drawable canvas with a user-defined coordinate system. FloatCanvas supports mouse and keyboard events which can be bound to items drawn on the canvas.

GDAL [7] is a translator library for reading and writing raster geospatial data formats, such as digital elevation model. GDAL also comes with a variety of useful command-line utilities for data translation and processing. An example of using the GDAL library in WiPlan is for showing the elevation at the mouse cursor. Every time the user moves the mouse, wxPython fires a mouse move event. The method bound to this event uses the coordinates of the mouse cursor to read the elevation from a digital elevation model using the GDAL library.

As the software grew more complex, it became clear that a suitable software pattern needed to be followed. WiPlan employs the Model-View-Controller (MVC) pattern [110] [122] as it manages the complexity of WiPlan while isolating the domain logic from the graphical user interface.

The pubsub library framework is used to pass messages around WiPlan. With pubsub, the programmer designates publishers and subscribers of messages. Publishers and subscribers do not communicate directly; each message published has a topic and will be received by any subscriber to that topic. For example, if wxPython registers a mouse click event on the map, that mouse click event could be associated with a Python method that publishes a message with a specific topic.

This would be regarded as occurring in the view part of the MVC pattern and the pubsub framework acts as the controller in this case. An appropriate method in the model part of the MVC pattern could then be subscribed to that specific topic and as such, that method would be called. The pubsub framework is mainly used for dealing with GUI events.

The model-view-controller (MVC) pattern was first proposed by Trygve Reenskaug at Xerox PARC in 1978 [110]. The MVC pattern provides a software architecture that isolates the domain-specific model from the graphical user interface (view) via one or more controllers. The controller listens to events associated with the view, such as a mouse click, and invokes the associated action in the model.

The model may then inform the controller that it has been updated and therefore the controller may inform the view to update. For example, when the user wants to look at the site properties for a particular site, the view creates a mouse click event that is then received by the controller. The controller then obtains the site specific information from the model instance for that site, and finally informs the view to show the site properties information window with that specific information.

The implementation of the model-view-controller (MVC) pattern in WiPlan involves a main controller with seven sub-controllers that are responsible for providing communication between four major models and the view. Figure 7.1 shows the relationship between the models, controllers and view. In some cases, predominantly GUI events, it was necessary to make use of the pubsub message passing framework.

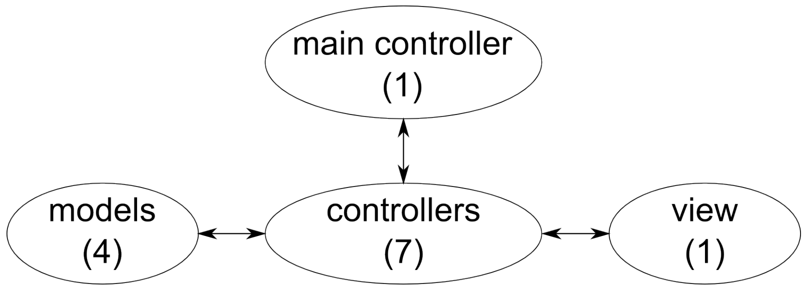


Figure 7.1: Model-view controller architecture of WiPlan showing lines of communication.

The main controller is responsible for the creation of the other controllers and for the common tasks of loading, saving or exporting a plan. The main controller creates seven sub-controllers which are: the elevation controller, external applications controller, hardware controller, WGS84 controller, site controller, link controller and coverage controller. Table 7.1 summarises the main controller class.

The elevation controller deals with elevation requests from the user interface and passes them on to the elevation model. The elevation model can then read the elevation from a digital elevation model and return it to the elevation controller. Table 7.2 and Table 7.3 show the elevation controller and the elevation model classes respectively.

MainController: Class
coverage_controller: CoverageController elevation_controller: ElevationController external_apps_controller: ExternalAppsController hardware_controller: HardwareController link_controller: LinkController load_dialog: NoneType save_dialog: NoneType selected_region: NoneType site_controller: SiteController timer1: Timer view: View wgs84_controller: WGS84Controller
exportKML() exportPlan() exportReport() getDirs() loadPlan() loadPlanGivenName() newPlan() onAutosave() regionsChosen() saveEnable() savePlan() savePlanGivenName()

Table 7.1: Main controller class.

ElevationController: Class
default_model: NoneType final_model: NoneType model: NoneType
cellHeightRequest() elevationRequest() getDefaultModel() getModel() setModel() worldBoundingBoxRequest()

Table 7.2: Elevation controller class.

ElevationModel: Class
cell_height: int cell_width: int dataset: NoneType origin: tuple world_bounding_box: list
getCellDimensions() getOrigin() getWorldBB() lookUp() setDataset()

Table 7.3: ElevationModel class.

The external applications controller is responsible for initiating processes external to the wxPython interface of WiPlan. For example, when a user creates a link, then the external applications controller invokes the path profile tool to determine line-of-sight. The external applications controller is also required for when the user creates a coverage plot or explores the local area. Table 7.4 shows the class diagram for the external applications controller.

ExternalAppsController: Class
dialog: NoneType keepGoing: boolean progress: NoneType running: boolean
coveragePlot() explorerExtract() geospatialExtract() isRunning() linkProfile() onTheFlyLOS() progress() run() start() stop()

Table 7.4: ExternalAppsController class.

The hardware controller is responsible for maintaining an internal list of interfaces and antennas. These lists are modified when the advanced configuration tools are used. When a link is created, the antennas and interfaces used are chosen from these lists. Table 7.5 shows the hardware controller class.

HardwareController: Class
antenna_specifications: dict interface_specifications: dict
getAntennas() getInterfaces() loadAntennas() loadInterfaces() setAntennas() setInterfaces()

Table 7.5: Hardwarecontroller class.

The WGS84 controller is responsible for converting coordinates between the WGS84 projection and the chosen projection of the country or region where the network is being planned. In the case of New Zealand, the WGS84 controller converts coordinates between WGS84 and the NZTM projection [12] using the WGS84_NZTM model. Table 7.6 and Table 7.7 show the class diagrams for the WGS84 controller and the WGS84_NZTM model respectively.

WGS84Controller: Class
model: WGS84ModelNZTM
WGS84ToNative() nativeToWGS84() setModel()

Table 7.6: WGS84controller class.

WGS84ModelNZTM: Class
WGS84ToNZTM() NZTMToWGS84()

Table 7.7: WGS84ModelNZTM class.

The site controller is responsible for the creation, modification and removal of sites. The site controller creates an instance of the site model, described in Section 7.2, when the user places a site. Table 7.8 shows the site controller class. The site controller is responsible for accessing the relevant information from the site model instance for that particular site when the user accesses the *site properties information window*. The site controller maintains a Python dictionary of sites, indexed by a unique identification number. The site controller also calculates site costs and adds link configurations to sites.

SiteController: Class
adjacency_list: list adjacency_lock: Lock antenna_specifications: list canvas: MapCanvas climate: WeatherModel connectivity_graph: Graph current_id: int interface_specifications: list link_controller: LinkController main_controller: MainController nodes: dictionary parent: Parent sites: dictionary sites_lock: Lock tutorial_mode: boolean view: View
addLinkController() calculateRelayCost() calculateSourceCost() getAdjacentSites() getSites() loadSites() nodeCreate() plotCoverage() setAntennaSpecifications() setInterfaceSpecifications() setTutorialMode() siteAddUnallocatedInterfaceWithAntenna() siteCreate() siteModify() siteRemove() updateSiteCost() updateTotalCost()

Table 7.8: SiteController class

The link controller is responsible for the creation, modification and removal of a link. The link controller creates an instance of the link model when the user creates a link between two sites. Table 7.10 and Table 7.11 show the link controller and the link model classes respectively. The link model contains the sites that the link connects and the status of the link; whether it is connected to a source, or if it is line-of-sight or non line-of-sight. The link controller is responsible for accessing the relevant link information when the user accesses the *link profile information window* for a particular link. The link controller is also responsible for calculating the link budget and determining the equipment that should be used for a link. The link controller maintains a Python dictionary of links, indexed by a unique identification number.

The coverage controller is responsible for the creation and removal of coverage plots. The coverage controller creates an instance of the coverage model when the user creates a coverage plot. The coverage model contains the details necessary to overlay the coverage plot image on the map in WiPlan. Table 7.9 shows the coverage controller class.

CoverageController: Class
canvas: MapCanvas coverage_plots: dictionary current_id: int main_controller: MainController parent: Parent scale: NoneType view: View
createCoverage() removeCoverage() setScale()

Table 7.9: CoverageController class

LinkController: Class
canvas: MapCanvas connections: dictionary connectivity_dialog: NoneType current_id: int currently_selected_link: LinkModel link_line_temp: NoneType links: dictionary los_ready: int main_controller: MainController profile_list: dictionary site_controller: SiteController start_id: int tutorial_mode: boolean view: View
calculateOrientation() calculateTilt() check80211a() check80211b() checkHouse() connectionCreate() drawTempLink() findHouseAntennaSpec() findHouseInterfaceSpec() linkBudget() linkEnd() linkLOS() linkProfile() linkProfileReadData() linkRemove() linkStart() linkSuccess() linkUpdate() loadLinks() recommendHardware() setLinkModel() setMode() setPoleHeight() showProfile()

Table 7.10: LinkController class.

LinkModel: Class
channel: int clutter_los: boolean distance: int frequency: int id: int sites: list state: int
computeDistance() getClutterLoss() getID() getSites() getState() setClutterLoss() setID() setState()

Table 7.11: LinkModel class.

7.2 Internal data structure of a site

In this section, the internal hierarchical data structure that WiPlan uses for describing a wireless *site* is discussed. Figure 7.2 shows the class diagram that represents the structure of a wireless *site*. In this discussion, the physical components (including technical aspects) of a *site* will be emphasised. Corresponding data structures will not be emphasised and will be proceeded with data structure. For example, a wireless *site* is represented by the site data structure.

There are several attributes that need to be stored for a particular *site* within the site data structure. A *site* should have a name that is meaningful to the people of the area (often the surname of the landowner is used). WiPlan will automatically allocate a default name for a *site* unless the user enters their own site name. A *site* also has a type, indicating whether the *site* is a source, relay or house, which is decided by the user when the *site* is created. The site data structure also contains location information such as coordinates in the appropriate map projection and the terrain elevation at that location. This location information is automatically stored by WiPlan when the user creates a *sit*e at a location.

When a *site* is a house or source, then the site data structure allows free-form textual notes to be stored by the user. When the *site* is a relay, instead of free-form notes, the site data structure allows for placement-specific notes and access-specific notes. The site data structure contains information about the pole height for mounting antennas and the calculated cost of the site. Predicted weather data for the *site*'s location is stored automatically by WiPlan–data includes lowest sun hours per day, highest rainfall and maximum wind speeds. WiPlan creates a system data structure for each site which represents all of the equipment that makes up the *site*.

The system data structure contains a list of all the host data structures that represent the *hosts* in the *site*. The system data structure also contains details of the type of power source and whether a switch is used. WiPlan will determine whether a switch is necessary and which *host* types are required. The user is responsible for specifying the type of power source available i.e. mains power. A *host* is a small, generally low-power computer such as a Soekris [19]. WiPlan contains a list of *host* types that should be pre-loaded by the distributing ISP. Additionally, the user can add *host* types to this list. The host data structure has name, type and asset tag attributes, as well as an attribute for whether a *solar controller* is used by the *site*. The host data structure is responsible for the list of *interface* types that the *host* has - for most devices this is one or two, though there are devices that can have more.

An *interface* is the radio card that fits inside the *host*. The interface data structure has a name and asset tag, as well as a reference to an interface specification data structure. The interface data structure represents the actual instance of the *interface* whereas the interface specification data structure contains all the general details about the *interface* such as price. The interface data structure contains details such as protocol, transmit and receive losses particular to the type of *interface* and *antenna*. The distributing ISP is responsible for pre-loading WiPlan with a list of *interface* specifications. Again, the user has the ability to add specifications using the advanced interface configuration tool. The interface specification data structure contains details such as the type of the *interface*, the price, the size and the form factor, such as mini-PCI. The interface specification data structure contains a list of *protocol* types supported by that *interface*.

The protocol data structure has a name that represents the actual *protocol*, such as 802.11a, and has lists of supported *bit rates* and supported *channels*. The bit rate data structure contains a 3-tuple of information detailing the *bit rate* itself, as well as the associated *transmit power* and *receive sensitivity*. The

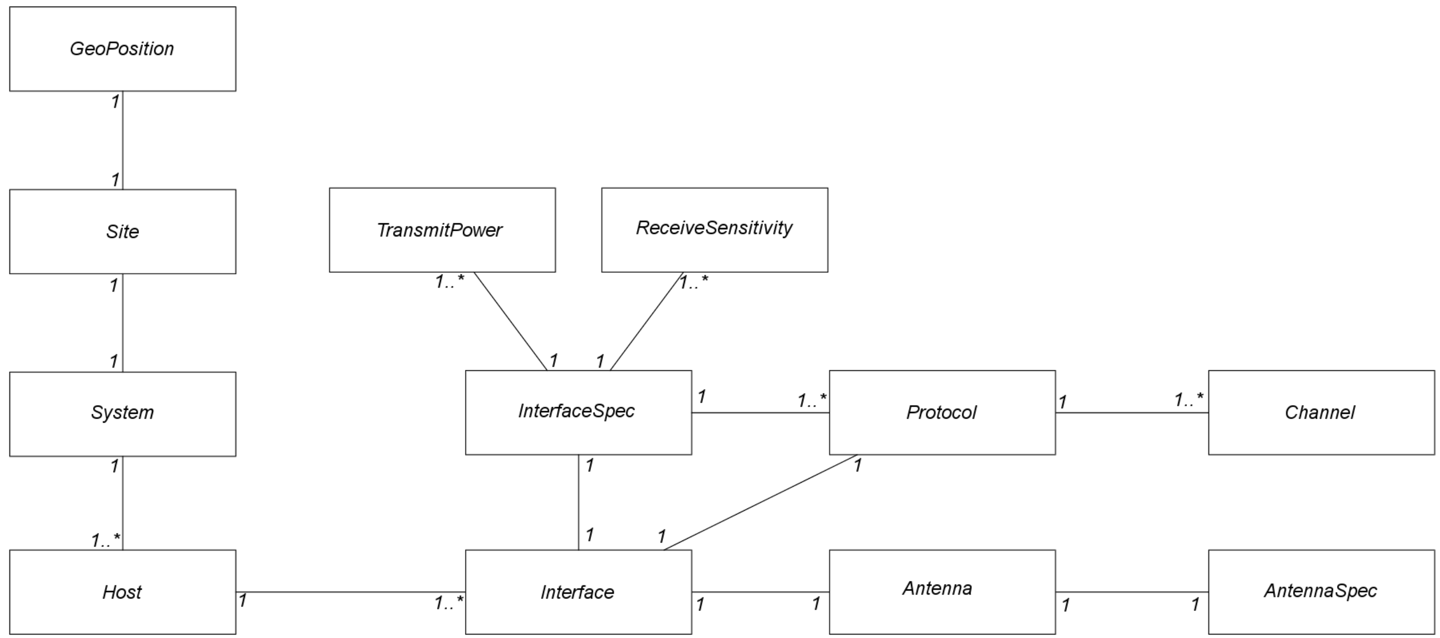


Figure 7.2: Class diagram showing the site data structure.

channel data structure contains the *channel* identification number, the centre frequency of the *channel* and the width of the *channel*. *Protocol*, *bit rate* and *channel* information are all provided as part of the *interface* specification.

As with the *interface*, an *antenna* also has a data structure representing the *antenna* instance and a data structure representing the *antenna* specification. As with *host* and *interface* specifications, the distributing ISP is responsible for pre-loading WiPlan with a list of *antenna* specifications; the user can modify and add *antenna* specifications using the advanced antenna configuration tool. The antenna data structure has an asset tag and a reference to the antenna specification data structure. It also has details about the height of the *antenna* up the pole, the orientation of the *antenna* and the tilt of the *antenna*. The antenna specification data structure contains details about the type of *antenna* including the name of the *antenna* and type of the *antenna*, such as parabolic. The specification stores the gain of the *antenna*, the azimuth or angle of direction in the horizontal plane and the elevation or angle of direction in the vertical plane. Finally, the antenna specification data structure stores the frequency range supported by the *antenna* and the *antenna* price.

7.3 Chapter summary

This chapter discussed the libraries that WiPlan used and described the internal architecture, including how a site is represented, of WiPlan.

Chapter 8

Expert evaluation

The WiPlan user interface was evaluated using two approaches: expert evaluation and user testing. This chapter describes the expert evaluations that took place and the findings of those evaluations. Expert reviews were conducted to evaluate usability and functionality before evolving to user testing. This included two usability expert reviews and one wireless network planning expert review.

A *heuristic evaluation* is a method for finding usability problems in a user interface design where a small set of evaluators examine the interface and judge the compliance of the interface with recognised usability principals, or heuristics [102]. Heuristic evaluation is described as a one of the “discount” usability engineering methods and is suitable for use early in the usability engineering life cycle to identify usability problems in the user interface [103]. Heuristic evaluation was chosen due to being inexpensive relative to other evaluation methods [104] and having a faster turn-around time than user testing [90].

An *expert evaluation* is a heuristic evaluation where the evaluators are deemed experts in their field. Different evaluators find different problems and so multiple evaluation results can be aggregated to give a substantial set of usability problems. Research shows that expert evaluation finds more minor problems than other methods such as user testing [84]. Minor problems are often not seen in user testing, though still have a negative impact on usability [102]. Evaluators pay more attention to identifying major usability problems while not neglecting minor problems when evaluating an interface [102]. Expert evaluators were used to quickly identify these usability problems so they could be addressed before progressing to user testing.

Nielsen categorises evaluators in to three groups: *novice* evaluators with no usability expertise, *regular* usability experts, and *double* usability experts who also had experience with the particular type of interface being evaluated [102]. Nielsen explains that regular experts would identify more usability issues than novice evaluators and double experts would identify the most issues; he notes, however, that double experts are hard to come by [102]. Molich et al. warns against conducting heuristic evaluation with end users as evaluators, as end users do not have sufficient knowledge and understanding of usability principals [100].

The results of two types of expert evaluation are presented in this chapter. The first is a conventional usability heuristic evaluation where **two independent HCI experts** examined WiPlan according to recognised usability heuristics such as those described by Nielsen [101]. Two usability expert reviews were conducted by regular HCI experts for this research. The second type of expert evaluation presented here involved a **wireless network planning expert** examining WiPlan according to their expectations of functionality. According to Nielsen, the wireless network planning expert would be a novice evaluator with respect to usability. This, along with the two conventional evaluations, totals three independent usability evaluations which meets the number recommended by Nielsen for identifying usability problems [104].

8.1 Usability heuristics

Nielsen's heuristics [101] are probably the most popular usability heuristics for user interface design and are used to justify the usability problems identified and presented in Section 8.2. A summary of Nielsen's heuristics are as follows:

Heuristic 1 - Visibility of system status The interface should always keep users informed about what is going on, through appropriate feedback within reasonable time.

Heuristic 2 - Match between system and the real world The interface should use words, phrases and concepts familiar to the user, rather than technical terms. The interface should present information in a natural and logical order.

Heuristic 3 - User control and freedom Users should feel in control and that every function should have an "emergency exit".

Heuristic 4 - Consistency and standards The interface should follow platform conventions and that users should not have to wonder whether different words, situations, or actions mean the same thing.

Heuristic 5 - Error prevention Users should be presented with a confirmation option before committing to an action and careful design should prevent problems from occurring.

Heuristic 6 - Recognition rather than recall The user's memory load should be minimised by making objects, actions, and options visible. The user should not have to remember information from one part of the dialog to another and instructions for use of the system should be visible or easily retrievable whenever appropriate.

Heuristic 7 - Flexibility and efficiency of use Accelerators, such as special dialogs, may be used that may speed up the interaction for the expert user such that the system can cater to both inexperienced and experienced users.

Heuristic 8 - Aesthetic and minimalist design Dialogs should not contain information which is irrelevant or rarely needed. Every extra unit of information in a dialog competes with the relevant units of information and diminishes their relative visibility.

Heuristic 9 - Help users recognize, diagnose, and recover from errors Error messages should be expressed in plain language (no codes), precisely indicate the problem, and constructively suggest a solution.

Heuristic 10 - Help and documentation Help and documentation should be focused on the task and should be easy to use.

8.2 HCI expert reviews

The expert reviews were conducted by two independent academic experts in the field of HCI to identify any problems associated with the design of the WiPlan user interface. These experts were not involved in the development or design of WiPlan, and did not have any previous experience with WiPlan prior to the expert reviews. The researcher was present at both expert reviews and the same process was followed for both evaluations. The process firstly involved the expert stepping through the WiPlan tutorial and mentioning any usability issues as they were encountered; these issues were recorded by the researcher. Once the expert completed the tutorial, they were then asked to have a second closer look at the main interface, the *site properties information window* and the *link profile information window*, and to comment on any further issues. The entire process was audio recorded and the researcher took manual notes. Both expert review sessions lasted approximately one hour to enable the expert to carefully step through the tutorial and discuss any issues that were encountered.

8.2.1 Expert review one

The first expert reviewer was a Senior Lecturer in HCI in the Computer Science department at The University of Waikato. The expert review took place in the expert's office using the laptop that WiPlan was developed on. The researcher recorded audio and made manual notes as the expert conducted the review. Most of the changes made to address the issues identified by the expert involved minor alterations unless otherwise mentioned in the following discussion.

A small number of similar problems were found relating specifically to the tutorial. There were some inconsistencies between the text shown in the tutorial and text else where in the interface, such as labels and buttons. These inconsistencies match heuristics 2, 4 and 10. The role of the tutorial is to provide help and documentation while presenting words, phrases and concepts familiar to the user. The user should not have to wonder whether different words mean the same thing. The inconsistencies were identified and fixed.

The expert identified a problem affecting heuristics 1 and 4. The problem was that when the user ticked the "This link has no obstructions" check box in the *link profile information window* (area B, Figure 8.2), a computation in the order of seconds would take place before the tick showed in the check box. This was fixed to provide instant feedback that the check box had been ticked while following check box conventions.

Several inconsistencies and standard violations in the interface as a whole were identified (heuristic 4). The expert identified that the name of the *link profile information window* and the link profile plot were inconsistent, which has since been fixed. He found that the antenna buttons in the *link profile information window* were originally labeled as “Raise antenna height” (areas C & D, Figure 8.2) but in some cases, the user may wish to lower the antenna height. Therefore, the button labels were changed to “Adjust antenna height”. He also discovered that many of the buttons and menu items opened dialogs that required further information from the user. He explained that it was standard practice in user interfaces to place an ellipsis (. . .) after the name of the button or menu item to indicate this. The appropriate buttons and menu items were adjusted to contain an ellipsis suffix.

The expert pointed out that the northing and easting coordinates in both the status bar and the site dialog lacked units, which were consequently added. He mooted that the map controls should be similar to those of Google Maps; this is a possible feature for future work. He also noted that the icons used for representing sites required more of a professional look. The icons were modified to have a matching background with different identifying icons in the foreground which gave the icons a professional look (Figure 8.1). He pointed out that the items in the menu bar were not standard and should be modified to match a user interface standard. As WiPlan was developed in Ubuntu, the menu items were modified to meet the GNOME human interface guidelines [49].

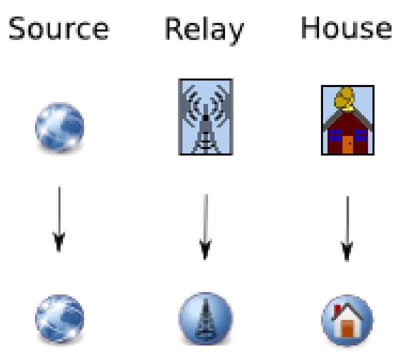


Figure 8.1: Icons

Inconsistencies that could lead to user misunderstanding were identified (heuristic 5). The expert felt that it was important to highlight that the weather information in the site dialog (area C of Figure 8.3) was estimated or predicted weather and not real live data. The wording was changed to prevent the user misunderstanding that the weather was estimated, such a misunderstanding could lead to an error of judgment. He also suggested introducing a cost for antenna height, as a user would not realise the implications that antenna height might have on the network design without an antenna height cost being included. An additional fixed cost per metre was added to address this.

Early in the development history of WiPlan, read-only text fields were used to display static information in the *site properties information window* (area B, Figure 8.3) and the Link profile dialog (areas A, C & D, Figure 8.2). He explained that the user may believe that these text fields can somehow be edited and that the user may try to discover how they can edit the text fields. He advised that these text fields should be changed to labels to avoid causing user confusion and consequently this advice was followed.

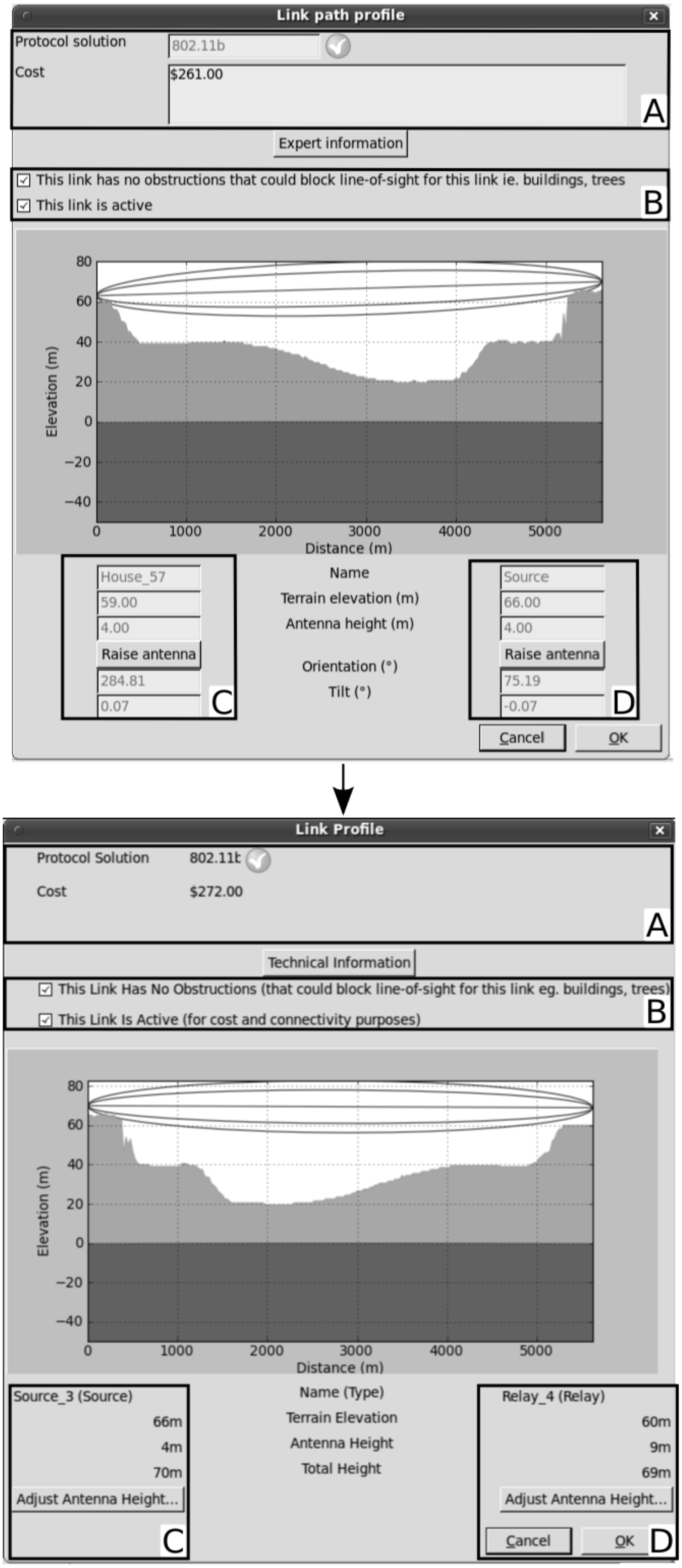


Figure 8.2: Link Profile dialog

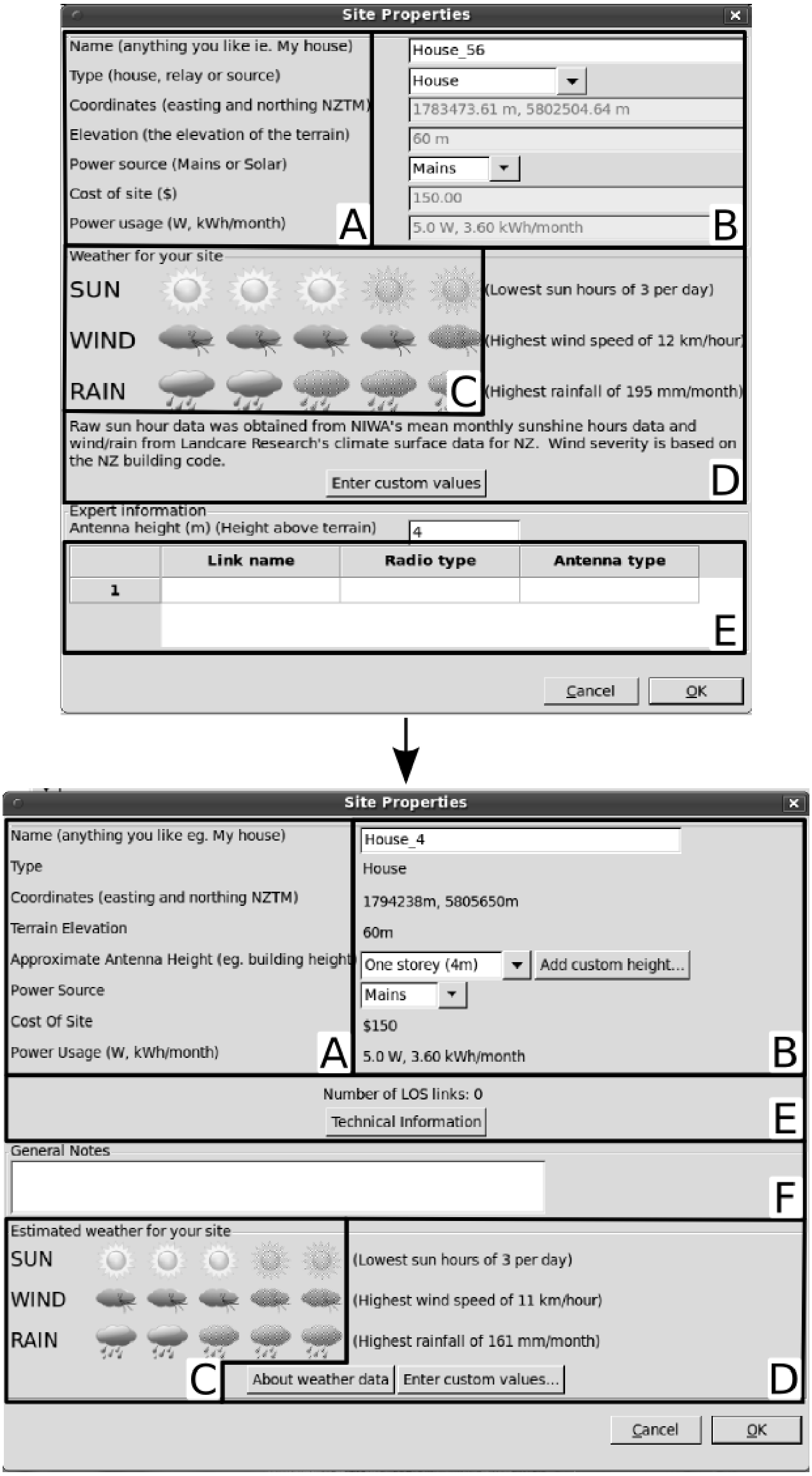


Figure 8.3: Site properties information window

The expert made some suggestions to help reduce the load on the user's memory by making key information easily retrievable (heuristic 6). He suggested that though the user may not want to know the details about the links from the current site, it would be useful for the site dialog to contain a label showing the number of links that were connected to that site (area E, Figure 8.3). In the connectivity dialog, he pointed out that it would be useful to have the type of site listed for each end of the link (areas C & D, Figure 8.2), as the name might not be enough for the user to recall the site types. He suggested that when the user hovers the mouse pointer over a site, it is more useful to the user to display the name of that site rather than the elevation at that point. All of these suggestions were implemented in WiPlan.

Issues were identified that affected the aesthetics and minimalist design of the interface (heuristic 8). The scale on the main interface used a serif font which made it difficult to read, so the expert pointed out that a sans-serif font should be used. He found the image used for the compass rose on the main interface to be too complex and requested that it be replaced with a simpler image (Figure 8.4). He also found that the line thickness of line-of-sight indicator, shown when the user is creating a link, was too great and that it made the line-of-sight indicator look imprecise. The thickness of the line was reduced resulting in a sharper line.

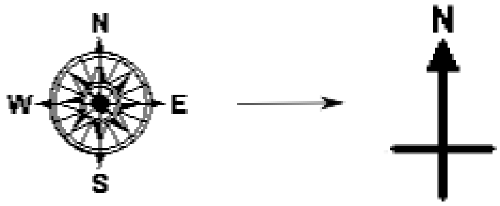


Figure 8.4: Compass rose

Issues that affected the aesthetics and minimalist design of the *site properties information window* were also found (heuristic 8). The expert observed that a drop-down list should only be used for three or more choices, and that radio buttons should be used for the power source as there are only two choices.

The drop-down list was retained as there are multiple forms of power sources and it may be desired that these be added to the list of power sources. For example, wind or water power sources may be available. In the second revision of the *site properties information window*, extensive explanation text was added (areas A & D, Figure 8.3). He pointed out that some of the explanation text was unnecessary and that the *site properties information window* was becoming cluttered, hence the text identified as being unnecessary was removed. He suggested that the text and icons in the weather panel were too close together (areas C & D, Figure 8.3) and that the set custom values dialog for weather was over-sized. As a result, extra space was inserted between the text and icons in the weather panel, and the set custom values dialog was re-sized.

The expert also observed some issues that affected the aesthetics and minimalist design of the *link profile information window* (heuristic 8). Most of these issues related to the layout of the widgets in the *link profile information window*. He suggested that the information for the sites on the left and right (areas C & D, Figure 8.2) should be centre-aligned with their respective y-axis of the link profile plot. He also suggested that the labels with numeric data should be right-justified with zero decimal places, and that a total height label be added so that the user can match the total height to the height shown on the link profile plot (areas C & D, Figure 8.2). He observed that the dialog information above the link profile plot was too close to the edge of the dialog and that the information should be indented (area A, Figure 8.2). These recommended changes were implemented in WiPlan and required significant restructuring of the *link profile information window* (Figure 8.2).

The final issue that the expert identified affected heuristic 7. In order for the system to cater to expert users, WiPlan needs the functionality to export the network plan to a common format for sharing with other members of the community and the network planning expert from the distributing ISP. To address this issue, functionality was added to WiPlan to export the network plan to an image file with details of the sites and links written to a text file report. The capability of exporting the network plan to KML for use in Google Earth and Google Maps was also added. Implementing export functionality required significant effort.

8.2.2 Expert review two

The second HCI expert was a Professor of the Graduate School of Library and Information Science at the University of Illinois. The issues identified by expert one were fixed before expert review two commenced. The second expert review took place in the expert's Waikato office using the laptop that WiPlan was developed on. The researcher recorded audio and took manual notes as the expert conducted the review.

The expert identified issues affecting the usability of the tutorial. He pointed out that when a tutorial changed to the next step, the change was not obvious to the user (heuristic 1). Also some steps of the tutorial transition to the next step halfway through the text explanation, leading to confusion on the part of the user and possible error (heuristic 5). He suggested that subsequent text be moved to the next step in order to avoid confusion. He pointed out that when referencing a check box, it should be addressed by name, even if it is the only check box (heuristics 2 and 4). He also mentioned that dialogs should be referred to as windows for user familiarity (heuristic 2) and that the tutorial should be sized such that scroll-bars are not required (heuristic 8). These recommendations were all implemented in WiPlan and required minimal effort to implement.

The expert also found some issues with the other parts of the interface. He pointed out that in the site dialog for a relay site, the access and placement dialogs should have the same title as the respective button text (heuristics 2 and 4). He suggested that when the user clicks compute coverage for a site, they should be prompted with a simple Yes/No dialog in case they clicked it by accident. As the coverage computation takes a few seconds to run, the user might get confused and/or frustrated (heuristics 3 and 5). These recommendations were all implemented in WiPlan with minor effort. He also noted that the blurry lower-resolution maps outside of the area of interest may confuse users (heuristic 5). This issue could be addressed using a pyramid map scheme, as in Google Maps but this is outside the current scope of this research.

The expert noted ideas that would allow flexibility and enhance the efficiency of use (heuristic 7). In the *link profile information window*, he mentioned that it would be useful to have emphasis of an obstruction (if an obstruction exists) in the link profile plot, such as zooming in on the obstruction. This suggestion has not yet been implemented in WiPlan as it would require extensive restructuring of the *link profile information window*. The expert also pointed out that being able to click at a point on the link profile plot and have WiPlan create a relay at that point would be useful. He suggested that when the user hovers the mouse point over a link, then the interface should show the cost of that link. Finally, he explained that in the site adder dialog, it would be clearer to the user if the x and y labels changed based on the selected coordinate type. For example, if the selected coordinate type was NZTM, the labels would be easting and northing. If the selected coordinate type was WGS84, then the labels would be longitude and latitude. The last three suggestions were implemented in WiPlan with minor difficulty.

8.3 Wireless network planning expert review

The wireless network planning expert review was conducted by the chief technical officer of a local ISP with ten years experience in wireless network planning in rural areas. The role of this expert was to identify any problems associated with the functionality of WiPlan and comment on the user interface design where appropriate. The expert conducted the review from both the point-of-view of a network design expert and the point-of-view of a user. He was not involved in the development or design of the WiPlan interface, and did not have any previous experience with WiPlan prior to the expert review.

He firstly answered a set of questions asked by the researcher. The expert then stepped through the WiPlan tutorial, commenting on functionality and usability issues as they were encountered. Once he had completed the tutorial, he was asked about his experience and any suggestions he might have for refinement. The expert review session lasted approximately one hour and took place in the expert's office using the laptop that WiPlan was developed on. The researcher recorded audio and made manual notes as the expert conducted the review.

No changes were made to the software as a result of this expert review because the suggestions were primarily implementation changes geared towards wireless network planning experts and would require a significant restructuring of the WiPlan planning process. If implemented, the suggestions could encourage planning experts to use the tool and could form part of future work. Unfortunately other wireless network planning experts were not able to be consulted in the time-frame available. It would however be interesting to obtain expert reviews from other wireless network planning experts to see if their opinions concur and restructure WiPlan as appropriate as part of future work.

8.3.1 Persona discussion

The expert was asked to comment on the realism of the personas and make any suggestions. Overall, he felt that the personas were reasonably realistic though optimistic with reference to real users that he has previously dealt with.

The farmers The expert commented that it is more typical that the farmers have to use online tools for managing their farms rather than actually wanting to do it, though there are some farmers pushing online tools. Eventually farmers get fed up using dialup and begin asking for something faster. The expert pointed out that video Skype is popular in the farming community. Skype is generally popular between grandparents and grandchildren, as the grandchildren are away from home studying or traveling.

School principal The expert stated that “I do not think I have ever met that school principal” but felt in a few more years that would probably change. He explained that most school principals are not so comfortable using computers and it is usually younger teachers pushing the technology. He has seen some use of video conferencing between fully-integrated schools and tertiary providers but not so much between schools. He did point out that most principals are heavily involved with and strongly loyal to their local community.

Community representative The expert commented that this is a realistic persona and he has certainly seen community representatives and gamers except he is yet to meet someone that is both a community representative and a gamer.

Cultural representative The expert pointed out that they have always dealt with an intermediate person rather than someone of kaumātua status. This intermediate person tends to be a younger trusted person in direct contact with kaumātua who has the technical ability to understand some of the technology and what the network will bring to the people. The concept of using video conferencing to communicate with people that have moved away from the community is quite strong. He stated that it is very important that someone like this persona is involved as it is difficult to predict from external sources what is allowed and what is not.

8.3.2 Pre-tutorial discussion

The expert pointed out that the ’average’ client they deal with are “fairly motivated people that can’t get decent broadband” and would go out of their way to achieve decent broadband. He explained that most clients know little about how wireless networks work but that most of them are using computers and they are frustrated at not being able to get a fast enough Internet connection. Client occupations range from farmers through to people trying to run businesses.

The expert felt that the persona motivations behind wanting decent broadband were realistic. He explained that in order for the software to support the personas, “the most critical thing for the people is going to be determining coverage” and identifying the trade-off between cost and coverage. He also stated that given "a set of users that want to be connected, [the software needs to assist in] determining the best way to connect those users".

He explained that helping to find the likely locations for placing sites by being able to take a set of addresses and compute connectivity and coverage from those addresses is necessary for rural wireless network planning.

8.3.3 Post-tutorial discussion

Once the expert completed the tutorial, he was asked about his experience. He pointed out that he found zooming difficult using the zoom tools on the tool bar. He had to ask the researcher how to zoom as he was so used to using the mouse wheel for zooming in and out. He stated that when placing a site, it is desirable to be well zoomed in but still be able to observe the two sites that the link connects. “I suppose the difficulty is around working with things at multiple scales, appropriate to the task. Being able to swap between those modes or having a bifocal display might be a useful thing.”

He stated that WiPlan is “nice in that its purpose built for explicitly creating wireless links and seems to be giving good feedback” and that there are useful features in there that are specifically targeted at wireless network planning. He stated that “a lot of the other mapping tools [don’t] do things as well” and that creating a link between two sites and being informed that line-of-sight is obstructed is “really nice”.

Finally, the expert considered whether they would use WiPlan for planning rural wireless networks and he responded that it "would need to be a lot more polished but certainly a tool with [those] sorts of features" would be useful. He commented that WiPlan "still seems quite clunky but it is nice with the feedback about whether links are going to work".

8.3.4 Recommendations

The expert had recommendations relating to features of the interface.

The maps The expert explained that "the problem with a satellite map [is that] you lose where you are very quickly, where as with a topographic map [there is] quite a bit of text on there [showing] where things are". He noted that the explore local area dialog looked nice but being able to manipulate sites in a Google Earth type fashion would be more useful. He suggested the use of a rainbow colour scheme for the terrain, so that the user is to determine the relative heights of hills and that as long as there is a legend, users would be able to understand the colour scheme.

The line-of-sight indicator The expert suggested that the line-of-sight indicator could be improved by determining when the mouse is stationary and while the mouse remains stationary, repeatedly computing line-of-sight with progressively finer resolution terrain data. Computation would cease once the mouse was moved and the process would begin again. He also mentioned that "what some of the other tools do [is] break it up and give immediate feedback on where the obstructions are". This is a way of showing along a link path where in that path has line-of-sight to the transmitter. For example, Radio Mobile does this by showing the terrain profile as green where there is line-of-sight from the transmitter and red where there is not.

The link profile information window The expert stated that it would be rare for the right place to position a relay to be on the direct path between two sites, referring to the ability to place a relay by clicking on the link profile plot in the *link profile information window*. He explained that the user would wanting to explore off to the sides of the direct path and that putting a site on that line seems arbitrary". He also pointed out that having the location of the mouse indicated on the map when moving along the profile would be useful. This is essentially a real-time version of placing a relay via the link profile plot but showing an indicator on the main map rather than creating a relay site.

Other The expert noted that having the easting, northing and elevation shown in the status bar was "quite nice". He did express concern about the sections on placement and access in the *site properties information window*, stating that he wondered how much the sections on placement and access would be used and how useful they will be.

8.4 Chapter summary

This chapter discussed concepts for conducting an expert review of the WiPlan user interface and presented the results of three expert reviews. This chapter explained what an expert review is and the reasons for conducting one before introducing Nielsen's heuristics for evaluating user interfaces. The results of two expert reviews by experts in human-computer interaction with reference to Nielsen's heuristics were presented and the responsive actions described. Finally a network expert conducted an expert review and found that the tool "is nice with the feedback and things you are getting about whether links are going to work". The network expert also had suggestions for improving functionality aspects of the user interface.

Chapter 9

Evaluating WiPlan in the wireless network planning process

In this chapter, the use of WiPlan in wireless network planning is explored. A novel study design using role-playing is described for evaluating how WiPlan assists with planning a wireless network. The chapter presents the findings of the two trials undertaken following this study design. The chapter concludes with a summary that explores the impact of WiPlan on the wireless network planning process and how the study design influenced this process.

9.1 Study design

WiPlan was designed to facilitate a planning process appropriate for a rural community, which is most likely to take place as an informal meeting at someones home. WiPlan does not include explicit support for collaboration but is intended to support synchronous, co-located work with a relaxed social setting. It is anticipated that snacks and refreshments would be provided, and that a computer with WiPlan would be connected to a TV or projector for community members gather around and plan their community network.

This study is designed to simulate such a meeting taking place as setting up a real meeting that could be observed is impractical. A real meeting may take place over more than one day and rural communities that want broadband access for their area are typically located a significant distance from urban areas. The advantage of simulating the meeting is that an area with an existing network that is known to the researcher can be chosen where the situation is fully understood, allowing reliable evaluation of the solutions discovered by the participants.

The presence of an existing network shows that a viable solution exists and the researcher can use their local knowledge of the area to evaluate how well local knowledge was solicited. Rather than using real people from the area who may already have the wireless network and be biased by it, people can be selected from outside the area. Essentially, there are two alternative options::

- Conducting a user study in an area where a wireless network already exists and the local area is known. This option would be prone to bias by the existing network.
- Conducting a user study in an area where a wireless network does not exist. This introduces uncertainty about the local area and the feasibility of a wireless network.

Role-playing offers a third alternative where the certainty about an existing network and the local area is established but bias is eliminated by selecting people from outside the area. Role-playing is commonly known as the practice where a person changes their behaviour to assume that of another person or character in a fictional setting. Role-playing has been used in literature to help solicit information and promote sharing of that information [51, 53, 64, 115]. Dionnet et al. [64] used a role playing game to raise awareness among farmers about a joint irrigation project. The approach allowed experimental exploration of decision making and supported the solicitation of information from the farmers and the sharing of that information. This is important because as part of this methodology, the aim is for the participants to make decisions in consultation with each other and to share their knowledge of the local area.

Camargo et al. [53] discuss how to use role-playing games to train people about specific aspects of new and difficult to understand legislation relating to land and water management. They point out that decision making is not only based on logic-formal thinking but also mobilises emotive and affective elements as in real life. The informality of a game also reduces tension and provides a relaxed atmosphere. Camargo et al. state that the cooperation effort is essential to perform the required tasks. This highlights the importance of providing a relaxed atmosphere so that people are comfortable to discuss issues and participate in making decisions.

The study described in this chapter has been established as a novel role-playing game where the game participants work together to plan a wireless network for their community. The study design involves a group of five people using WiPlan to plan a wireless network for their local community. As with the comparable work of Dionnet et al. [64], the aim is for the participants to make decisions in consultation with each other and to share knowledge of the local area. The informality of a game environment and availability of refreshments helps to create a relaxed atmosphere.

To establish a role-playing game for wireless network planning, the personas from Chapter 6 were further developed to provide characters for the study participants to role play. There is a dairy farmer, a school principal, a community representative, a kaumātua[1] and a farmer that runs a mixed sheep and beef farm (herein referred to as the sheep and beef farmer).

[1] kaumātua are respected elders who are the keepers of the knowledge and traditions of the family, sub-tribe or tribe [48].

WiPlan users are anticipated to be middle-aged people with low to moderate comfort using computers. These users may have some academic background, such as the school principal, though most users are likely to have grown up and worked in the local community. These characteristics have been identified through discussions with the wireless network planning expert and by meeting locals from the CRCnet and Tūhoe networks.

The setting of the study is a real location - the Te Whāiti valley in the Urewera ranges, New Zealand. The Te Whāiti valley was chosen as the setting for the following reasons:

1. Te Whāiti is isolated and surrounded by large mountains (the Ureweras). This is appropriate as WiPlan is aimed at building wireless networks for connecting isolated rural areas to the Internet.

2. Te Whāiti has a rich Māori history and has many sites of cultural significance. WiPlan has been designed such that cultural beliefs and sites of cultural significance can be considered when planning a wireless network.

3. Te Whāiti has villages, a school and farms whose occupants are reflected by the five personas.

4. Te Whāiti already has a wireless network installed by Rurallink, linking Minginui and the school to the Internet. This is the network that operated by Tūhoe Online and discussed in Section 1.2.1. This existing wireless network provides a network solution to compare with the plans created in this study. Also, the expert who planned the Tūhoe network is available to comment on these plans.

5. The researcher has *some* local knowledge of the Te Whāiti area as he has visited key parts of the existing wireless network. He met locals and gained a hands-on appreciation for the mountainous terrain. This is useful as the researcher was able to design a study with a realistic setting and determine accurate user characteristics.

Figure 9.1 shows a map of the Te Whāiti area. Each person participating in the user study received this map of the area (Figure 9.1) and a unique set of information, appropriate to their persona, for them to peruse. Information included the layout and heights of nearby buildings and vegetation as well as facts specific to the persona. Some of this information was intentionally irrelevant to the wireless network planning process and some of the information is purposely imprecise to realistically model local knowledge. Participants were allocated a budget of how much money their character were willing to spend to build the wireless network. The total budget was $18,000 for building the wireless network. The developed personas and associated information are available in Appendix D.

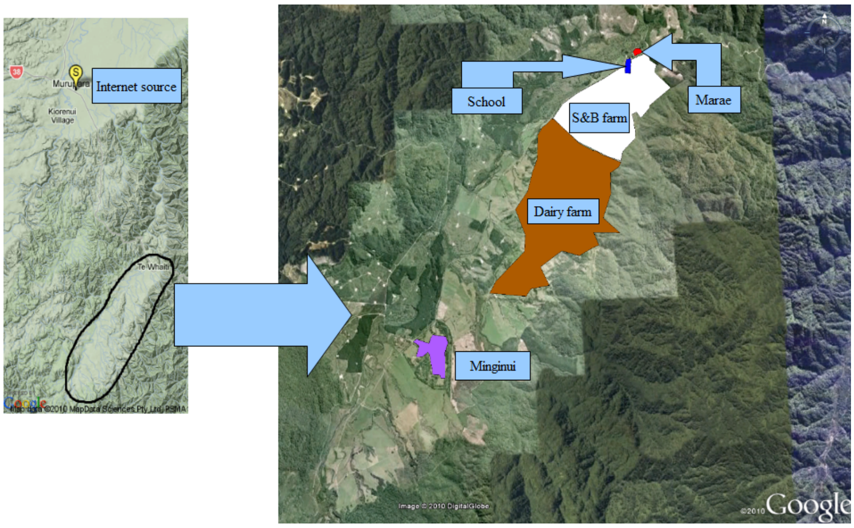


Figure 9.1: Main map of the Te Whāiti area used for study design

Two Māori experts were consulted to ensure that the persona of the cultural expert was respectful and that the cultural information was correct. The persona of the cultural expert was provided with Nga Taonga [2] of Ngāti Whare[3], to acknowledge and show respect for the local iwi[4]. Nga Taonga identifies the sacred mountains, river and forest of Ngāti Whare.

[2]the treasures.
[3]the local people of the Te Whāiti area.
[4]people.

The users had two main tasks to accomplish while role-playing their allocated characters. The first task was to follow through the tutorial in order to acquaint them with the software. The second task involved the users planning a wireless network to connect the Minginui village, the local school and each of the farmers' houses to the Internet. WiPlan was configured to load the correct maps for the Te Whāiti area and show the location of the Internet source, as indicated in Figure 9.1. The users then had to peruse their information to determine the locations of the houses, the school and Minginui village on the maps.

Two trials were conducted using this study design. In the first trial, computer science students were selected as participants for two reasons. The first reason is that as this was the first trial, there was the potential for unexpected software problems to occur. Computer science students are well-equipped to identify and deal with these problems. In some cases, computer science students can even resolve the problems.

The second reason is that computer science students are confident using computers and are willing to give feedback on the experience, which helps to ensure that there are no fundamental problems with the functionality of WiPlan while also testing out the study design. In the second trial, participants similar to the personas being role-played were selected. These participants were primarily non-academic, middle-aged people who were moderately comfortable using computers. They were not actually part of a rural community. All participants had minimal knowledge of wireless networks and rural wireless network planning.

There are three key questions that these trials are intended to answer.

1. Did the participants engage in role-playing their personas and collaborate on planning the wireless network?

2. Did the tutorial assist participants with decision making and trouble shooting during the wireless network planning process?

3. Were the participants able to plan a wireless network and draw out relevant local knowledge during the process?

The following discussion examines the findings of the two trials to provide answers to these questions.

9.2 First trial

The first trial was conducted in a group meeting room where the five participants could gather around a projector. One participant was selected by the group to be the computer operator. The session lasted two hours, including stepping through the tutorial, planning the network and taking a break for lunch. The participants actively play-acted their personas to the point that they enjoyed the experience while still providing valuable feedback.

All participants were male and the average age of participants was 20, ranging from 18 to 25 years old. Four of the participants were computer science undergraduate students and one was a doctoral computer science student involved in HCI research. Participants had minimal knowledge of wireless networks and no knowledge of rural wireless network planning. Participants had a high level of comfort using computers. Table 9.1 shows the characteristics of the participants for trial one compared to those characteristics identified for the target end-users in Chapter 6.

Characteristic	Target end-users	Trial one participants
Age	Will range in age from teenagers to 80+	18 to 25
Gender	Both male and female	All male
Ethnicity	All, primarily NZ European and Māori	NZ European
Education	May have only minimal education qualifications	All high school graduates
Occupation	Primarily agriculture, education or small business	Students
General computer experience	May have little or no prior experience with using computers	Very high level of comfort and experience
Spatial reasoning	Likely to be quite skilled with distances and heights	Likely to be quite skilled with distances and heights
Domain experience	Expected to have no prior experience with wireless network planning	Expected to have no prior experience with wireless network planning
Attitude	Positive and eager to work towards a community wireless network.	Enthusiastic.

Table 9.1: Characteristics of trial participants versus those of target end-users.

Figure 9.2 shows the layout of the room for the first trial. Two of the five participants, one of whom was the computer operator, sat at a desk facing the projector screen. The other three participants sat close behind the two participants at the desk. A single video camera recorded the session from behind the participants. WiPlan also recorded an event log of the study. Audio was not recorded for this trial. The researcher sat in the corner of the room where the computer was located. The operator used a wireless mouse and keyboard to control WiPlan. A projector was used to provide a large display that all of the participants could easily see. A TV or large computer monitor would also be appropriate if no projector was available. A large viewing device with reasonable resolution allows the participants to see planning details more easily in their shared space. Participants play-acted the personas defined in Appendix D for the entire duration of the trial.

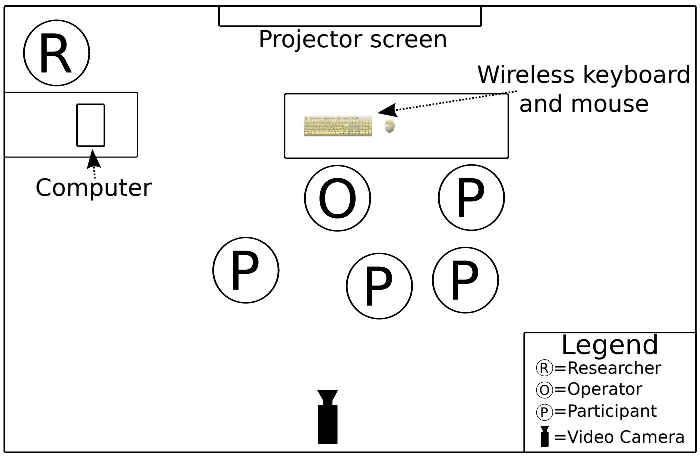


Figure 9.2: Room layout diagram for the first trial

9.2.1 Tutorial

The tutorial was successfully completed in nine minutes and 26 seconds, allowing an average of 26 seconds per step. This was quicker than expected but is not that surprising as the operator was comfortable using computers. Figure 9.3(a) shows a time-line of the tutorial steps completed. The time-line indicates that the tutorial was well-paced and that an even amount of information was introduced at each step. Most tutorial steps were completed relatively quickly (Table 9.2 shows the number of seconds that each step took for the participants to complete). Participants understood and completed 17 of the 22 steps quickly and easily.

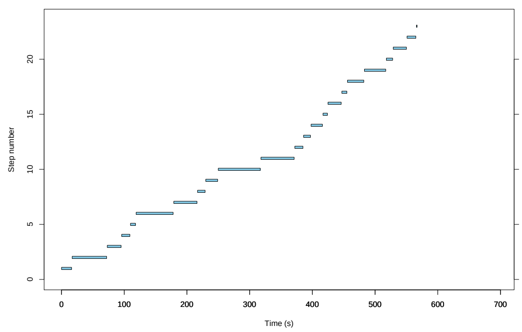
Five of the steps (2, 6, 10, 11 and 22) were a bit more involved and hence took somewhat longer to complete. Step 2 was the first view of the *site properties information window* and the users spent 56 seconds looking at the different information presented. Step 6 involved zooming in on the map and the operator had trouble zooming to the desired level. Figure 9.3(b) shows this 60 second use of zooming and panning, showing that the operator zoomed in too far and then had to correct themselves. This is most likely due to the implementation of zooming where significant delay is experienced between clicking the mouse and the zoom function taking place. It is therefore possible for the user to click multiple times without the map having had time to zoom to the correct level, so the user zooms in too far.

Steps 10 and 11 focused on placement and access for the relay site, requiring the participants to read help dialogs and write some notes so spending 68 and 54 seconds respectively on these steps is expected. Figure 9.3(b) shows the different map modes used during the tutorial. Apart from the use of zooming and panning for step 6 of the tutorial, only the default pointer mode was used for the duration of the tutorial.

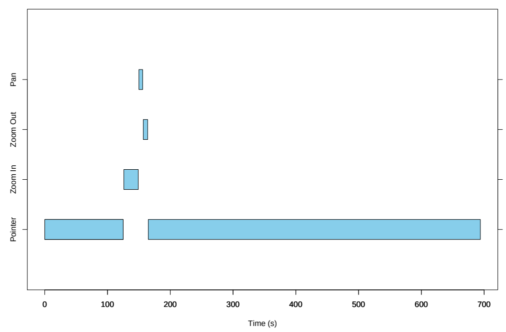
Step number	Seconds to complete
1	17
2	56
3	23
4	14
5	9
6	60
7	38
8	13
9	20
10	68
11	54
12	14
13	12
14	19
15	8
16	22
17	9
18	27
19	35
20	11
21	22
22	15

Table 9.2: Time taken to complete each tutorial step for the first trial

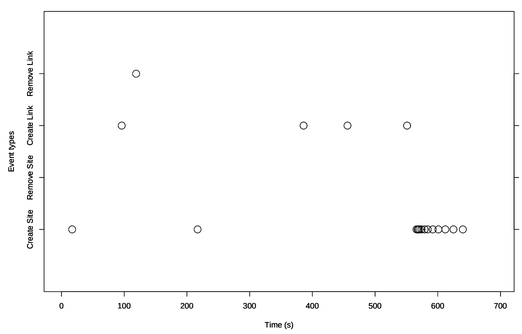
Figure 9.3(c) shows a time-line of tutorial events for the first trial. An event represents a site or link being created or removed. The events match what is expected from the tutorial except for the sites created at 500 seconds onwards. This is step 22 of the tutorial where the user is asked to place a relay by clicking on the link profile plot of the link profile information window. In this case, the user has not seen the *create relay confirmation dialog*, and has therefore clicked multiple times, hence creating multiple sites. This highlights that there is an usability issue with the confirmation dialog in that the placement and importance of the dialog were not obvious to the user. This is an implementation problem and should be addressed in future work.



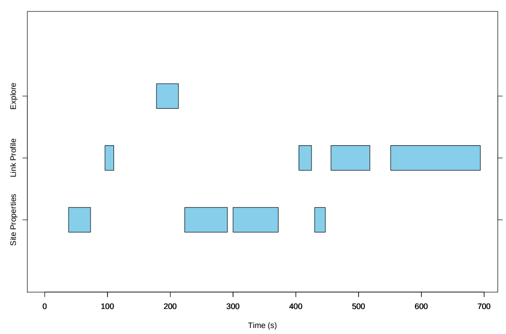
(a) Timeline of tutorial steps completed



(b) Timeline of map modes used during tutorial



(c) Timeline of site and link events during tutorial



(d) Time spent in information windows during tutorial

Figure 9.3: These graphs show the main actions of the participants during the tutorial of the first trial.

Figure 9.3(d) shows the time spent in each information window type. During the tutorial, the majority of time is spent in one of the three information window types. This indicates that the participants were comfortable with the tutorial steps involving the main interface as they are directed by arrows and other indicators but that the information windows are more detailed and therefore require more attention and decision-making.

9.2.2 Network plan

Figure 9.4 shows the final plan that the five participants successfully designed. The network planning task took approximately one hour and 28 minutes to complete. The plan contains one source (S1), three relays (R1, R2 and R3) and three houses (H1, H2, H3). The source, S1, is located in the township of Murupara and H1 is the local school. H2 and H3 represent the homes of the sheep and beef farmer and dairy farmer respectively. The participants successfully created a network plan that connects the local school, the farmers' houses and the village of Minginui to the Internet for a total cost of $10,743.

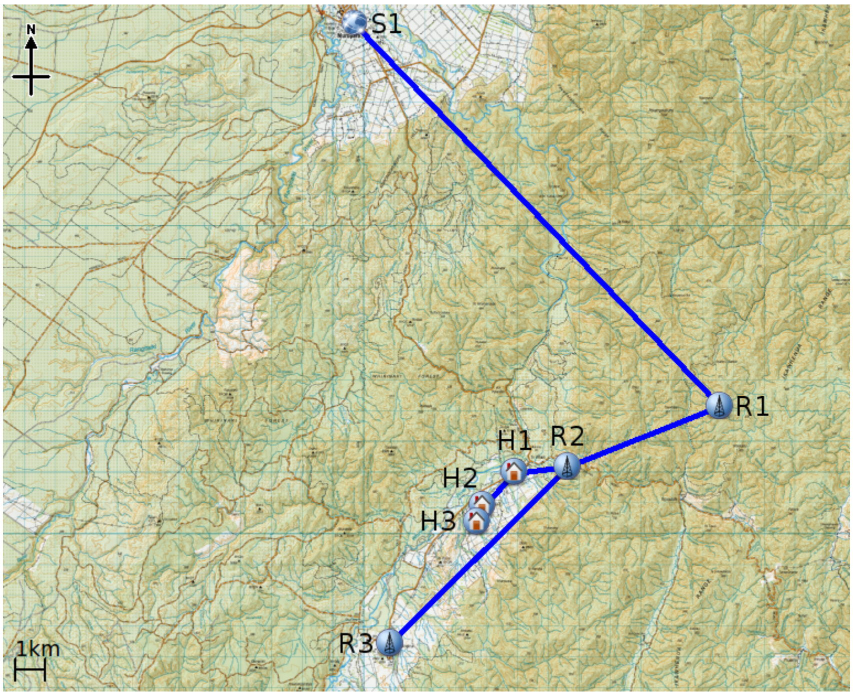


Figure 9.4: The final wireless network plan for the first trial

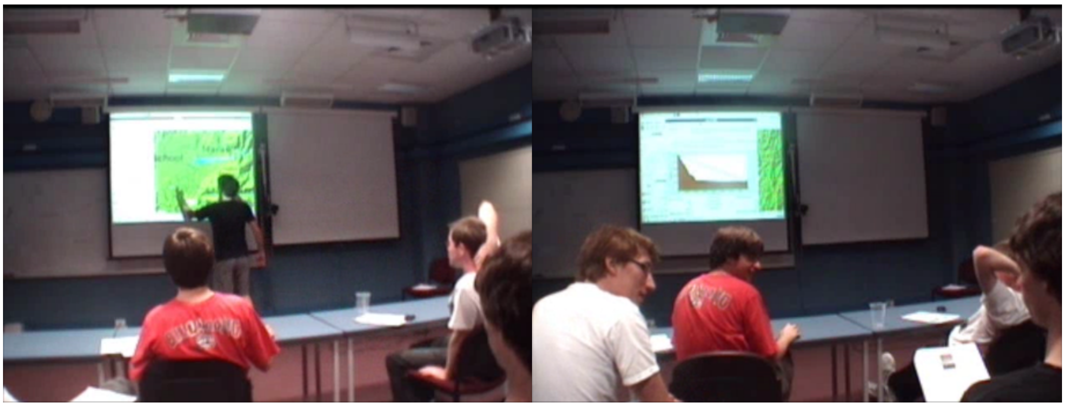
The participants in trial one starting following the multi-branch strategy discussed in Section 2.3.5 almost immediately. They were quick to make decisions and seldom back-tracked. Participants were at ease with creating sites and links. Their primary approach was to create several sites, link them together and then systematically adjust or remove them as they saw fit. Often the participants were quick to make decisions that should have been discussed in more depth. At the end of the trial, the participants discussed their final design and were happy with the plan they had designed.

9.2.2.1 Planning approach and decisions

Observations are used to describe the approach that the users took as audio was not recorded for this trial. The participants followed a fairly straight-forward strategy. They began by importing all of the houses. The participants then explored the area by panning around and zooming, as evident in Figure 9.6(b), before deciding to place relays at each of the trig station locations. The participants make frequent use of zooming but seem to avoid using panning where possible. This is most likely due to the inaccurate and laggy implementation of panning in WiPlan.

The participants then investigated their link options by creating links between sites to see where there was line-of-sight and what the different solutions would cost. Figure 9.6(c) and Figure 9.6(d) show this process where the participants are examining site and link details in the respective dialogs and progressively eliminating sites and links from consideration.

Figure 9.6(d) shows that participants tried using the *explore local area* feature twice but did not use it again. This, along with the level of frustration observed, indicated that they found it confusing and hence did not find it useful. The *explore local area* feature was intended to give a 3D visualisation of the local area however participants found that it was difficult to navigate and

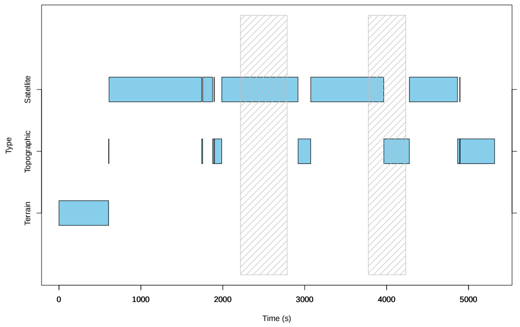


(a) A participant points out a location. (b) Participants discuss a non line-of-sight link.

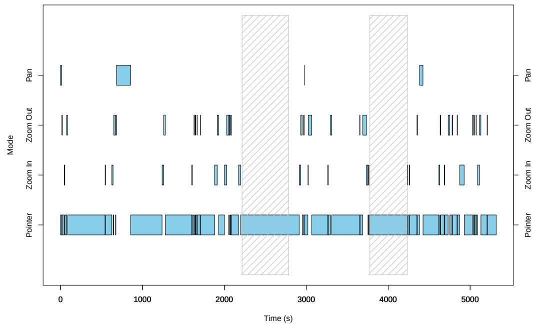
Figure 9.5: The participants in the first trial plan their wireless network.

did not convey any new information. The time that participants spent in the information windows is brief, indicating that they are concentrating their time on exploring the map.

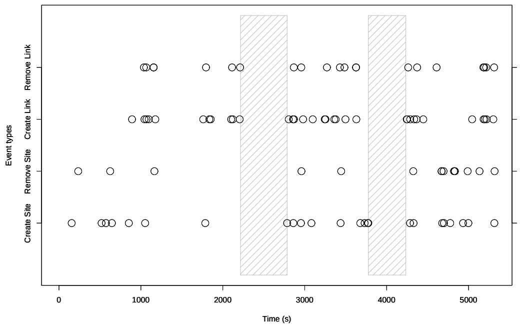
Participants use of the *link profile information window* was brief as the participants gained a good understanding of link line-of-sight issues and were able to make quick decisions about whether to adjust antenna heights or abandon a link. The time spent in the *site properties information window* was brief though reasonable for entering information about access and placement. Discussions about access and placement often took place before the *site properties information window* was accessed.



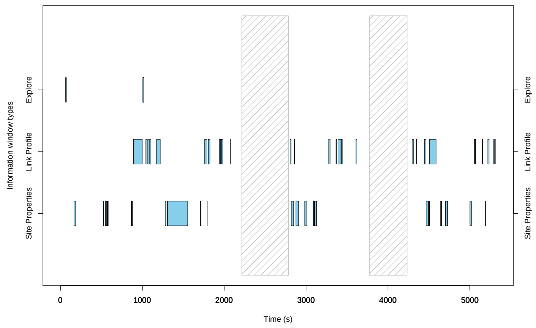
(a) Timeline of map background types used during the network planning process.



(b) Timeline of map modes used during the network planning process.



(c) Timeline of site and link events during the network planning process.



(d) Time spent in information windows during the network planning process.

Figure 9.6: These graphs show the main actions of the participants during the network planning part of the first trial. The shaded areas show where WiPlan crashed.

This process of finding a single relay site that is elevated above the rest of the terrain and then experimenting with other sites and links resembles the multi-branch strategy discussed in Section 2.3.5. Eventually this progression of elimination led to the final design shown in Figure 9.4.

Figure 9.6(a) shows a time-line of when the different map types were used and for how long. The satellite map was the most preferred with frequent changes to the topographic map and back again to the satellite map. This indicates that the topographic map was useful for obtaining information but that the participants were more comfortable with using the satellite map for exploration.

9.2.3 Local knowledge consideration for relay creation

Table 9.3 and Table 9.4 show the key attributes of the three relays. The participants explored the list of trig station sites that the community representative had as part of his information. They placed Relay R1 at a trig station site of the mountain known as Whakaipu which has an elevation of 1034 metres. Participants noted in the *site properties information window* that they had permission and that the best access would be via helicopter. It seems that the participants thought they were making an executive decision regarding placement, when permission from other parties would actually be required. Participants realised that getting the building materials to the site would be difficult due to poor access hence they chose to use a helicopter.

Relay	Trig site	Easting	Northing	Elevation
1	Yes	1935586m	5724102m	1034m
2	No	1930630m	5722148m	537m
3	No	1924869m	5716415m	368m

Table 9.3: A summary of the relays placed in the first trial identifying whether the relay was placed at a trig site and details of the geographic coordinates.

The participants also noted that the summit of Whakaipu could be accessed via a 3km motorbike track followed by hiking approximately 600 metres up the mountain. The participants determined that the antenna height at relay R1 needed to be 20 metres in order to have line-of-sight to the source S1 in Murupara. Building a 20m high antenna is somewhat unrealistic for a rural wireless network due to the costs involved; the fact that the participants were happy with the 20 metre antenna height indicates that the cost modeling of antenna height in WiPlan is insufficient. This would be addressed by incorporating more realistic cost modeling of antenna height in WiPlan and checking with the user whether the height infrastructure already existed. The participants chose relay R1 to be solar-powered. This choice is significant as it shows that participants considered mains power as an option and decided it was unrealistic to expect mains power at that location.

Relay	Antenna height	Power supply	Permission	Access
1	20m	Solar	Yes	Helicopter
2	4m	Solar	Unknown	4WD
3	10m	Mains	Unknown	Unknown

Table 9.4: A summary of the relays placed in the first trial identifying the antenna height and power supply, as well as detailing whether permission and access were considered.

The location of relay R2 was derived independently by the participants, who were unaware that the topographic map showed that it was a trig station site. This reinforces the assumption that trig sites are good locations to evaluate as initial sites. The elevation of the site is 537 metres and provides line-of-sight from relay R1 at Whakaipu in to the Te Whāiti valley. The participants determined that the antenna height should be four metres and that the relay should be solar-powered. An antenna height of four metres is reasonable and again, the choice of solar power indicates that participants considered mains power and decided it was unrealistic. The participants did not indicate that they had permission to place the site; however identified that the site could be reached with a 4WD. This indicates that the participants did not notice the steep terrain when considering how to access the site. Steepness is hard to gauge, especially when users are not familiar with contour lines. WiPlan would require maps that better illustrate steepness and/or some kind of steepness analysis to address this issue.

Relay R3 was placed on a barn in the Minginui village to provide Internet access to the village community. The barn is approximately 10 metres high and the site operates on mains power. The participants did not indicate whether they had permission or how best to access the site.

The placement and access information was not well used. Of the three sites, two sites had their best access type selected, one site indicated permission, one site had access notes and none of the sites had placement notes. Also, no general information was entered for any of the house sites or the source site.

This indicates that either the participants did not know what they should enter in these fields or that the fields were ignored. Either way, the importance of this information needs to be obvious to the user, and the requested information needs to be more specific than just empty text fields.

9.2.4 Usability issues

The kaumātua, who operated the computer, found that the "values are calculated with little user input which makes it fast to use" and that "the map controls worked well". Overall he thought that WiPlan "seemed to work really well for its intended purpose of designing wireless networks" though "stability and speed could be improved". The sheep and beef farmer said "I didn't use it directly but it looked easy to use. There were a couple of features that we didn't notice initially (importing site info, changing map types) but once we knew they were there we used them." He thought that "the software seems like it would be highly useful for planning a wireless network. In a couple of places, it looked like the user interface could use a bit of polishing, but that is to be expected from prototype software. As someone acting as a backseat driver it was easy to follow what was going on. It provided a good view of the layout of the network etc".

Main interface The researcher observed that the operator had difficulty with zooming and panning, mainly due to the lag involved. The researcher also observed that the operator tried to move sites by dragging them but this functionality is not implemented in WiPlan.

Site properties information window Participants created custom heights which were added to the drop-down list of heights but not selected by default. The participants then needed to select the newly created height in the drop-down list. The same custom heights were created for different sites raising the question of whether custom heights should be global between sites.

Other The researcher observed that participants did not have a realistic understanding of antenna height and that WiPlan did not highlight the extra cost that the antenna height contributed to the total cost. Participants found the *site adder tool* useful but were not aware of it until the researcher pointed out its existence. They found that the *site adder tool* did not add the entered names to the created sites, and that the coordinate type changed on each site added. This was identified as a software bug and fixed for the second trial. The WiPlan software crashed twice, raising the suggestion that an auto-save feature should be implemented. The reasons for WiPlan crashing were determined and later fixed before the commencement of the second trial.

9.2.5 Expert feedback

The chief technical officer of a local ISP with ten years experience in wireless network planning in rural areas (the wireless network expert introduced in Section 8.3) was asked to comment on the plan designed by the five participants. He was asked if the plan was feasible and he responded that the design was certainly going to be very challenging due to his knowledge of how steep the terrain is in the area but that it was certainly feasible. The participants were aware that the terrain was hilly and steep in parts but did not seem to fully comprehend the scale involved and how this affected wireless network planning.

He commented that the antenna height of 20 metres at Whakaipu (R1) would cost a lot more than the participants realised and more than WiPlan estimated. This indicates that cost modeling for antenna height should further investigated as part of future work so that the total cost can be conveyed to the user. The expert explained that Whakaipu (R1) would be a difficult site to access due to the deep dense vegetation and knowledge of the terrain in the area. He knew through consultation with the local community that Tawhiuau has a good walking track that was well used and that is one of the main reasons why the Tawhiuau site was chosen for the Tūhoe network. Another major reason for why it was chosen is that it can see through to the village of Ruatahuna.

Participants were aware of the terrain and vegetation however their opinion was that they could use a helicopter to access the site and that they could remove some of the vegetation. This shows that in future work, extra cost should be included by WiPlan when a helicopter is used for access. Removing vegetation may be more difficult than participants realised and in some cases may not be allowed.

He pointed out that there are possible problems when houses are connected to each other and that it is best to avoid this by connecting each house to a relay instead. Connecting the houses together also created the problem of a deep network with more potential points of failure. In future work, WiPlan should prevent houses being connected together unless the possible problems are presented to the user and accepted. The expert also commented that Minginui is surrounded by a shelter-belt and that any link in to Minginui would need to clear the shelter-belt. Including vegetation support in WiPlan as part of future work would help in such a situations.

9.3 Second trial

The second user study was conducted in a group meeting room where the five participants could gather around a projector. One participant was selected by the group to be the computer operator. The session lasted two and a half hours, including stepping through the tutorial and planning the network, though the participants did not finish planning the network. The participants play-acted their personas but were not as enthusiastic as the participants from trial one. They took the game quite seriously, adding a sense of realism to the trial.

Four of the participants were male, one was female and the approximate average age of participants was 50 years old. In comparison, the average age of participants in the first trial was 20 years old. Three of the participants were managers in building services, one was a student liaison officer and the other was an electrician. Participants had no knowledge of wireless networks or rural wireless network planning. Participants had a low level of comfort using computers, compared to participants from the first trial who had a high level of comfort using computers.

Table 9.5 shows the characteristics of the participants for trial two compared to those characteristics identified for the target end-users in Chapter 6. This comparison of characteristics shows that trial two participants can be considered representative of end users, particularly in terms of age, experience and comfort using computers.

Characteristic	Target end-users	Trial two participants
Age	Will range in age from teenagers to 80+	Estimated average age of 50
Gender	Both male and female	Both male and female
Ethnicity	All, primarily NZ European and Māori	NZ European and Māori
Education	May have only minimal education qualifications	Unknown
Occupation	Primarily agriculture, education or small business	Building maintenance managers, education, retired tradesman.
General computer experience	May have little or no prior experience with using computers	Little to some experience
Spatial reasoning	Likely to be quite skilled with distances and heights	Quite skilled with distances and heights
Domain experience	Expected to have no prior experience with wireless network planning	Expected to have no prior experience with wireless network planning
Attitude	Positive and eager to work towards a community wireless network.	Positive, slightly over-whelmed by task at hand.

Table 9.5: Characteristics of trial participants versus those of target end-users.

Figure 9.7 shows the layout of the room for the second study. This room was more suitable for meetings and had a large table that the participants could sit around. Two of the five participants sat on the left side of the table and the other three sat on the right side. All of the participants had to turn slightly to face the projector screen. Two video cameras recorded the session, one from behind the participants facing towards the projector screen, and the other facing the participants. WiPlan also recorded an event log of the study. Audio was recorded for this trial and was used to describe the planning process that the participants followed. The researcher sat in the back corner of the room. The computer was located under the table by the projector. The operator used a wireless mouse and keyboard to control WiPlan. Again a projector was used to provide a large display that all of the participants could easily see. Participants play-acted the personas defined in Appendix D for the entire duration of the trial.

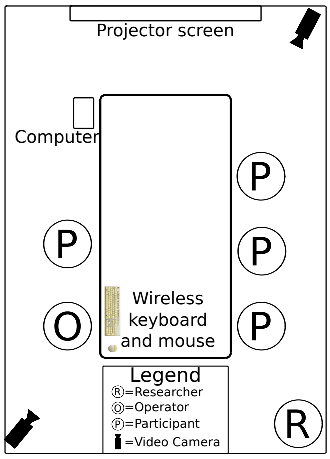


Figure 9.7: Room layout diagram for the second trial

9.3.1 Tutorial

The tutorial was successfully completed in approximately 27 minutes allowing an average of 71 seconds per step. This was slower than expected but the participants were careful, taking their time to ensure that they understood what was going on, so this is not that surprising. Also the level of computer confidence among these participants was similar to that anticipated for rural users, compared to the participants of the first trial. Figure 9.9(a) shows a time-line of the tutorial steps completed. The time-line indicates that the tutorial was well-paced and that an even amount of information was introduced at each step (Table 9.6 shows the number of seconds that each step took for the participants to complete). Participants understood and completed 13 of the 22 steps easily though carefully taking their time.

Figure 9.8: Participants engaged in the tutorial of the second trial

Participants had some difficulty with nine of the steps (1, 2, 7, 10, 11, 12, 13, 14 and 22). In step 1, the participants were asked to create a house site at the indicated location. Participants did not realise that the house had to be created at the indicated location for the tutorial to advance. This suggests that the tutorial wording may have been unclear and that the animated arrow indicating the location for creating the house site was not obvious. Step 2 was the participants first view of the *site properties information window* and so they spent some time to have a look at the different information presented. Participants had difficulty with exploring the local area in step 7. They did not know how to navigate around and expected to be able to move the existing site and create a new site. They also mistook the relay site for the house site.

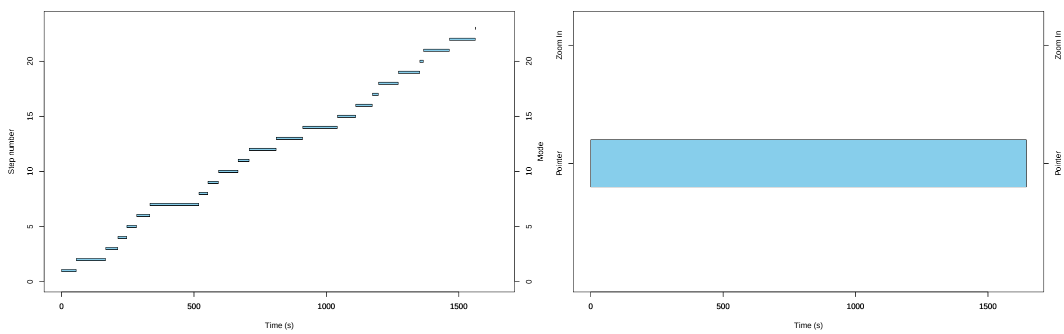
Steps 10 and 11 focused on placement and access for the relay site, requiring the participants to read help dialogs and write some notes so spending more time on these steps is expected.

Step number	Seconds to complete
1	56
2	111
3	46
4	34
5	37
6	50
7	185
8	34
9	40
10	74
11	42
12	102
13	100
14	131
15	69
16	63
17	23
18	75
19	81
20	14
21	98
22	98

Table 9.6: Time taken to complete each tutorial step for the second trial

In step 12, participants were zoomed too far out and did not notice the zooming functions therefore it took the participants some time to identify the potential link and then create a link. The zooming and panning tools were available in the toolbar but the participants did not notice them. This could be addressed by specifically introducing zooming and panning in the tutorial. Participants also had difficulty with steps 13 and 14 where they had to confirm that there were no possible obstructions and observe how the *link profile information window* changed. The participants were firstly confused that the obstruction was not immediately obvious and that they did not know the meaning of "protocol solution". They were then confused about having to click the check box, thinking that it should be checked automatically. It was not clear to the participants that terrain obstructions are different to obstructions such as vegetation and buildings. WiPlan needs to convey this difference to users more clearly. Finally, the *link profile information window* changes were not obvious to the participants and they had to check and un-check the check box three times to identify all of the changes. This could be addressed by identifying what parts of the *link profile information window* have actually changed in the tutorial so that the changes are more evident to the users.

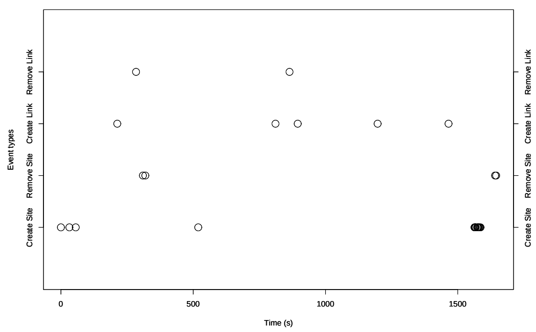
Figure 9.9(b) shows the different map modes used during the tutorial. Participants were unaware of the ability to zoom and pan so Figure 9.9(b) shows only the pointer mode being used. Again, the tutorial should specifically introduce the user to the zooming and panning tools. Figure 9.10(a) shows a time-line of site and link events that occurred during the tutorial. An event represents a site or link being created or removed. The events match what is expected from the tutorial except for anomalies at the beginning and end of the tutorial. Figure 9.10(a) shows that in step 1, the house was created three times before being placed in the correct spot to complete that step.



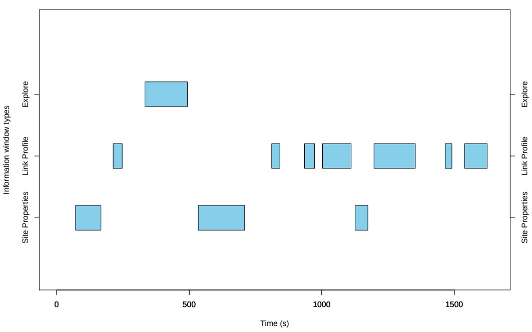
(a) Timeline of tutorial steps completed. (b) Timeline of map modes used during the tutorial.

Figure 9.9: Graphs showing a time-line of completed tutorial steps and map modes used during the tutorial of the second trial.

In step 22, at the end of the tutorial, the participants were asked to place a relay by clicking on the link profile plot of the *link profile information window*. In this case, the participants have not seen the *create relay confirmation dialog*, and the operator has clicked multiple times creating multiple sites. Figure 9.10(a) shows the creation of these sites. This highlights that there is an usability issue with the confirmation dialog in that the placement and importance of the dialog were not obvious to the user. Figure 9.10(b) shows the time spent in each information window type. During the tutorial, the majority of time is spent in one of the three information window types. As with the first trial, this indicates that the participants were comfortable with the tutorial steps involving the main interface as they are directed by arrows and other indicators but that the information windows are more detailed and therefore require more attention and decision-making.



(a) Timeline of site and link events during the tutorial.



(b) Time spent in information windows during the tutorial.

Figure 9.10: Graphs showing a time-line of site and link events, and time spent in dialogs, during the tutorial of the second trial.

9.3.2 Network plan

Figure 9.11 shows the final plan that the five participants successfully designed. Participants worked on the network planning task for approximately one hour and 22 minutes, though the allocated time for the study ran out before they could complete the task. The plan contains one source (S1), five relays (R1, R2, R3, R4 and R5) and six houses (H1, H2, H3, H4, H5 and H6). The source, S1, is located in the township of Murupara and H2 is the local school. The local marae is represented by H1. Though not directed to include the marae, the participants thought that they would connect the marae to the network. H3 and H4 represent the home and wool-shed of the sheep and beef farmer. H5 and H6 represent the home and milking shed of the dairy farmer. The plan had a total cost of $11,207.

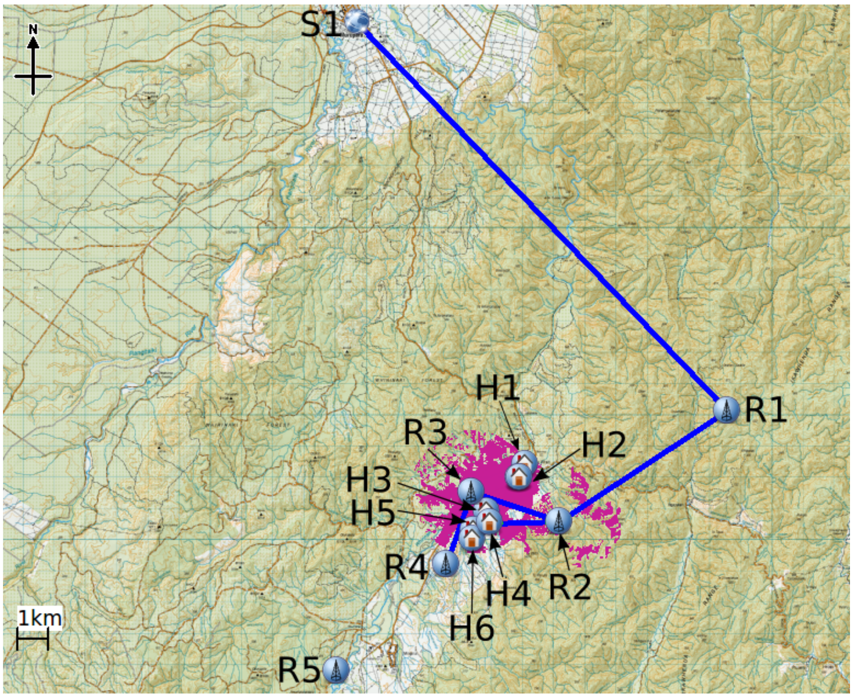


Figure 9.11: The final wireless network plan for the second trial

In general, the participants followed the multi-branch strategy discussed in Section 2.3.5. However, particularly earlier in the trial, they moved around map with no particular strategy and often back-tracked on decisions. As the trial progressed, the participants became more comfortable with each other, and began to discuss decisions more thoroughly before acting. The participants put quite a lot of thought in to their decisions and spent quite a bit more time on decision making than the participants in trial one. Participants were apprehensive and conservative about creating sites and links in contrast to participants from trial one who quickly created many sites and links in their design. As the allocated time ran out for the trial, the participants were not able to discuss their final design but they were quite impressed with the result.

9.3.2.1 Planning approach and decisions

The participants immediately started following the guide. Taking the guide wording literally, they decided that houses cannot be clustered as they are fixed in place and cannot be moved. This led to confusion on how to begin and what the actual task was. This indicates that the guide needs to be carefully worded to avoid confusion. After some group discussion and reading of their personas, they quickly figured out that they were building a wireless network to connect each of their homes to the Internet. The personas indicated that Internet connectivity was desired but did not explicitly state that the objective was to plan a wireless network to provide Internet connectivity.

The school principal suggested locating the village of Minginui. The dairy farmer and community representative pointed at the approximate area on the map, then the dairy farmer walked up to the screen and pointed out Minginui (Figure 9.12). The participants were not familiar with topographic maps but were able to determine the housing layout of Minginui. The school principal pointed out that the school needed to be connected and so the participants decided to locate the school and marae. While discussing the where the school and marae were, the kaumātua pointed out the location of Murupara, the Internet source of the network they were planning. The participants found the school and marae, and the school principal made the observation that there was at least one high hill between Murupara and the school.

The community representative then remembered his list of trig stations and commented that they are usually at the highest points but he was not sure what to do with the coordinates. The sheep and beef farmer remembered the *site adder tool* and the participants decided to use the *site adder tool* to add Whakaipu, the highest trig station on the community representative's list. After some confusion between NZTM and WGS84, the participants entered the details for Whakaipu in the *site adder tool.* The *site adder tool* should provide some explanation of NZTM and WGS84 including coordinate examples so that

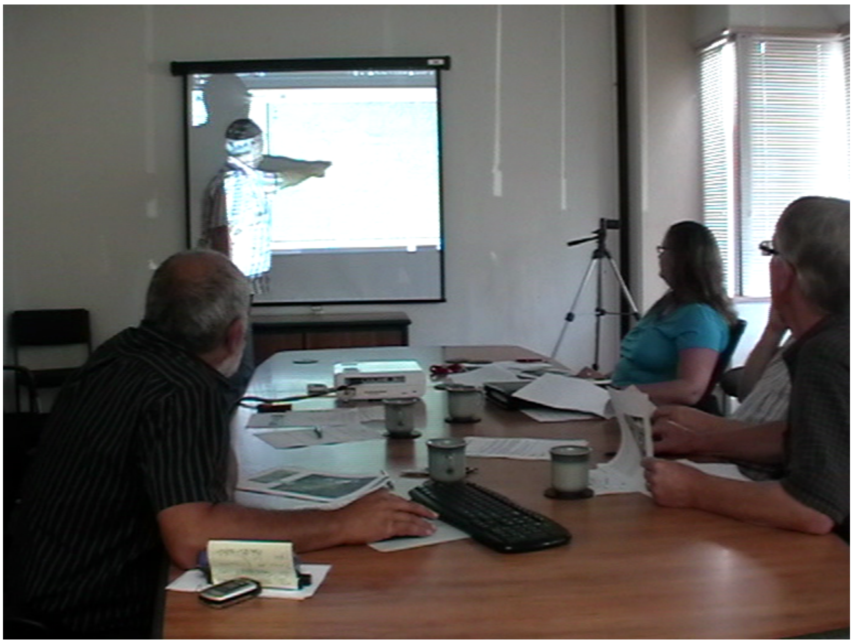


Figure 9.12: The dairy farmer identifies Minginui during the planning part of the second trial.

users are not confused. At first the participants thought the site was placed at the incorrect location until they viewed the *site properties information window* and the listed coordinates convinced them that the site was at the correct location.

The participants then tried to look at a link profile before they had created a link. They realised their mistake and created a link which then displayed the *link profile information window*. The operator tried to adjust the antenna height but accidentally clicked the main window, hiding the smaller height adjustment dialog. The researcher had to intervene and explain what had happened. This could be prevented by ensuring that the height adjustment dialog is modal so other windows cannot be selected. The participants decided to raise the antenna height of the Whakaipu relay site to 50 metres and then slowly reduce it. As they reduced the height, the kaumātua realised they could also adjust the height of the source at Murupara which might help. The participants had eliminated terrain obstructions but were confused that the link was still non line-of-sight, thinking that the check box should be ticked automatically (Figure 9.13). They eventually ticked the check box and the link became line-of-sight, yet the participants were still confused about what happened. The school principal shared his realization that extra relays increase the cost of the network and that WiPlan has a total network cost in the status bar.

The community representative pointed out that the participants needed to determine how Whakaipu might be accessed. After reading the access notes on his trig station list, the community representative stated that a helicopter would be required to deliver the building materials for building the site. It would be useful if WiPlan distinguished between access for building purposes and general access, as they may be different. House sites were then created at the marae, the school, the wool-shed, the milking shed and the farmers' houses using the site adder. The farmers decided that they would not consider the hay barns as potential sites. The participants then revisited the guide to figure out what they should do next. They decide to experiment with creating links between the existing relays and the houses. Several potential locations for relays are identified, some of which are created. Links are then created between the relay sites and the house sites but they all are obstructed and subsequently removed.

The community representative suggested investigating the remainder of the trig sites in list to which the other participants agree. First, the participants created a relay site at Tawhiuau and established a link back to the source. The link was obstructed near the summit and the participants decided that Tawhiuau was too far to the north, electing not to adjust the antenna and removed both the relay site and the link. The participants then tried placing relays at Te Reingaotemoko, Kopuatoto and Tikorangi, and creating a link from each to the source. All three were obstructed and the participants chose to remove them without experimenting with antenna heights. This indicates that the participants were not comfortable using the *link profile information window*. Automatic calculation of minimum antenna heights would have gone

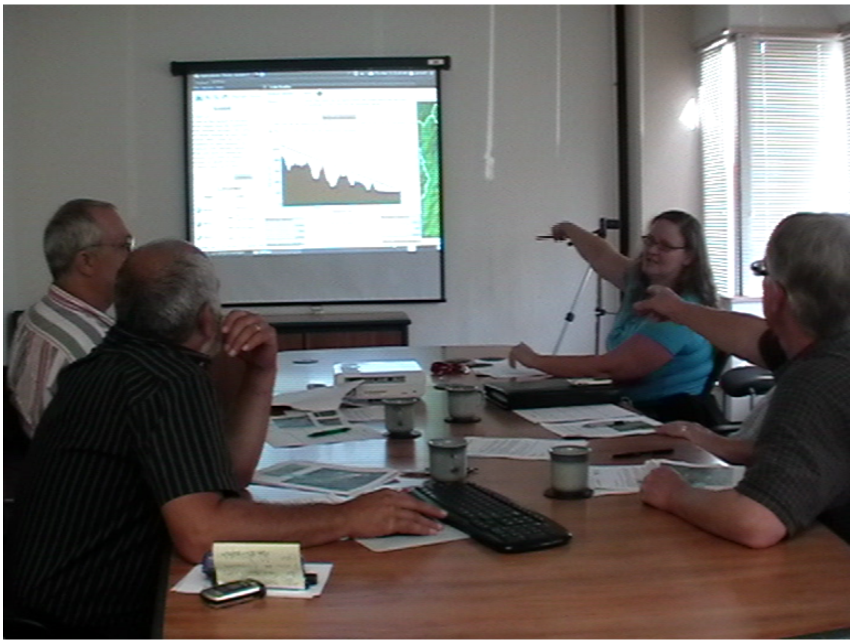


Figure 9.13: Participants discuss line-of-sight for a link during the planning part of the second trial.

a long way with these participants.

The participants returned to one of the trig sites identified earlier and created a relay there. The participants tried placing relay sites at different locations and establishing links to Whakaipu but they were all obstructed and the participants abandoned them. The map starting getting cluttered so the participants elected to remove some of the non line-of-sight links. The participants found a new high location using the elevation mouse helper and created a new relay site there. The participants found that there was a potential link to the school so they created a link between the new relay and the school. As the link was successful, the *line-of-sight confirmation dialog* was shown but the participants were confused as to why it came up. The operator clicked **no** to the *line-of-sight confirmation dialog* when it asked about possible obstructions and so the link remained non line-of-sight.

The sheep and beef farmer remembered about coverage and asked the operator to compute the coverage for one of the relay sites. The coverage seemed

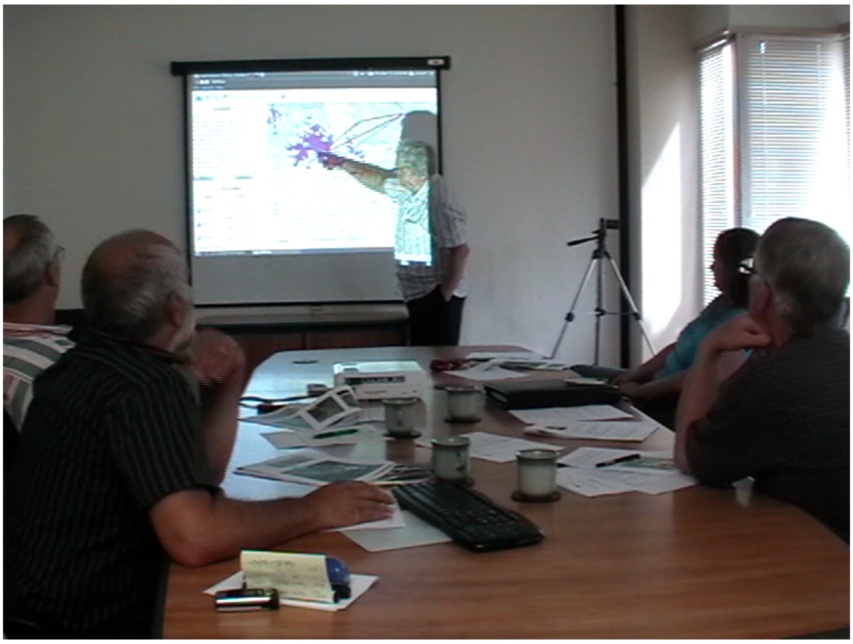


Figure 9.14: The community representative points out relay site coverage during the planning part of the second trial.

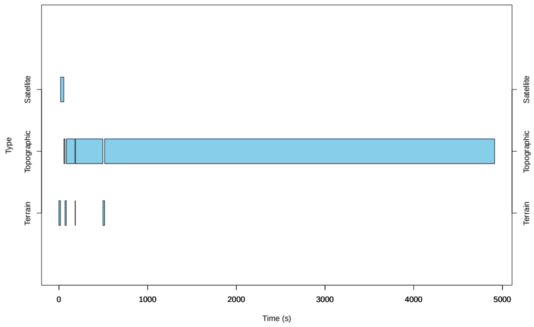
good and the kaumātua suggested that coverage might be a good way to determine how good a site location was. The participants created another relay site and computed coverage but this time the coverage was poor so they removed the site. They decided to return to the previous relay with good coverage and raise the antenna height. The operator accessed the *site properties information window* and entered five metres as a custom height, as the participants thought that the current height was zero metres when it was actually four metres. The operator recalculated the coverage, expecting to see an improvement but there was no difference. The participants noticed that two of the relays that they have placed provide good coverage of the northern part of the Te Whāiti valley (Figure 9.14).

The participants investigated new links but each time the link was obstructed and they gave up. Eventually they returned to one of the non line-of-sight links and look at the link profile. The participants then created a new relay (R2) by clicking on the link profile plot and computed the coverage. The coverage was poor but the participants decided to create a link between this new relay (R2) and Whakaipu. Participants were again faced by the *line-of-sight confirmation dialog*; this time they took a bit of a gamble and were delighted to see that the link was successful. The participants then created a link between relay R2 and a relay created previously (R3). The link was obstructed and the participants had difficulty at first identifying the obstruction. They raised one end to ten metres but the link still seemed obstructed. The participants realised that they had not ticked the check box, so they ticked the check box and the link succeeded.

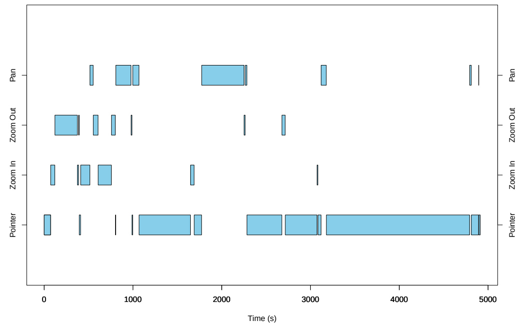
The participants recomputed coverage on the relay sites to determine that only some of the houses are covered. The school principal commented that they should remove some of the old redundant relays and links and explore how to get network connectivity to Minginui. The community representative pointed out a trig station on the topographic map and the operator placed a relay at that location (R4). The participants then decided to place a relay in Minginui and the operator panned down the map with some difficulty to Minginui. This is due to the inaccurate and laggy implementation of panning in WiPlan. The sheep and beef farmer identifies a trig station near Minginui as a good location for a relay. The operator created a relay at the trig station location (R5) and seconds later WiPlan crashed, just minutes before the session was due to end.

This process of finding a single relay site that is elevated above the rest of the terrain and then experimenting with other sites and links resembles the multi-branch strategy discussed in Section 2.3.5.

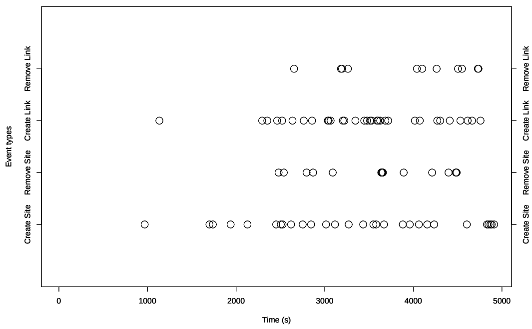
Figure 9.15(a) shows that the participants tried using the terrain map and the satellite map but were most comfortable with the topographic map. Figure 9.15(b) shows heavy interaction with the map between 0 and 1000 seconds, representing the initial period of exploration and finding Minginui and Murupara. Figure 9.15(c) shows that event activity was slight (between 0 and



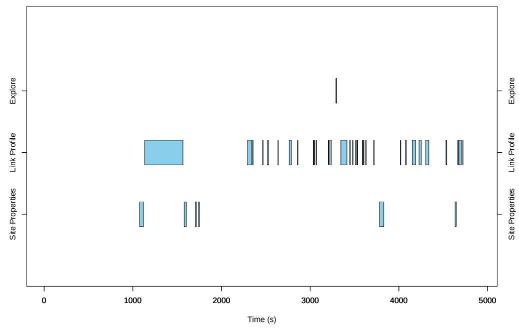
(a) Timeline of map background types



(b) Timeline of map modes used



(c) Timeline of site and link events



(d) Time spent in information windows.

Figure 9.15: These graphs show the main actions of the participants during the network planning part of the second trial.

2000 seconds) but after 2000 seconds, creation of sites and links was intense. Figure 9.15(d) reflects two interesting findings about this trial. The first is that between 1000 and 2000 seconds, the participants spend a significant amount of time in the *link profile information window*. This is the first link that the participants created and this reflects the difficulty they had with understanding how the link profile information window works. The second finding is that the participants repeatedly explored the link profiles of different links but only briefly. In that same period of time, the *site properties information window* was only viewed twice. This is most likely because failed links automatically display the *link profile information window*, forcing the user to consider why the link failed, whereas the user must decide that they want to view site properties for the *site properties information window* to be displayed.

9.3.3 Local knowledge consideration for relay creation

The key attributes of the five relays are shown in Table 9.7 and Table 9.8. The participants explored the list of trig station sites that the community representative had as part of his information. They placed Relay R1 at a trig station site on the mountain known as Whakaipu which has an elevation of 1034 metres. Participants noted in the *site properties information window* that the best access would be via helicopter as they realised that getting the building materials to the site would be difficult due to poor access. However the participants did not tick the permission check box or leave notes regarding placement. The participants actively discussed that the summit of Whakaipu could be accessed via a three kilometre motorbike track followed by hiking approximately 600 metres up the mountain but recorded no details in the access notes. Participants did not notice that the power source was set to mains power; the power source should have been set to solar power as it is unlikely that there would be mains power at that location. The participants determined that the antenna height at relay R1 needed to be five metres in order to have line-of-sight to source S1 in Murupara. They achieved this by raising the antenna at Murupara to 15 metres which is realistic as the Murupara antenna could be located on a high building.

Relay	Trig site	Easting	Northing	Elevation
1	Yes	1935586m	5724102m	1026m
2	No	1930190m	5720551m	684m
3	No	1927393m	5721516m	313m
4	Yes	1926578m	5719168m	407m
5	Yes	1923065m	5715772m	420m

Table 9.7: A summary of the relays placed in the second trial identifying whether the relay was placed at a trig site and details of the geographic coordinates.

The location of relay R2 was placed in scrub-covered hills on the eastern side of the valley. The elevation of the site is 684 metres and provides line-of-sight from relay R1 at Whakaipu in to the Te Whāiti valley. Relay R2 connects directly to the wool-shed owned by the sheep and beef farmer. Relay R2 also connects directly to relay R3. The participants determined that the antenna height should be ten metres which is high but not unreasonable. Participants did not notice that the power source was set to mains power; the power source should have been set to solar power as it is unlikely that there would be mains power at that location. The participants did not indicate that they had permission to place the site or identify the dominant form of transport to access the site. They also did not record any notes for placement or access. This indicates that the participants did not notice the placement and access areas, or did not think they were important. This could be addressed by WiPlan prompting the user to at least select the dominant form of transport and remind them about permission.

Relay	Antenna height	Power supply	Permission	Access
1	5m	Mains	Unknown	Helicopter
2	10m	Mains	Unknown	Unknown
3	10m	Mains	Unknown	Unknown
4	10m	Mains	Unknown	Unknown
5	4m	Mains	Unknown	Unknown

Table 9.8: A summary of the relays placed in the second trial identifying the antenna height and power supply, as well as detailing whether permission and access were considered.

Relay R3 was placed in scrub-covered hills at an elevation of 313 metres on the western side of the valley. Relay R3 is connected to relay R2 and relay R4. Relay R3 also provides coverage to the marae, the school, the dairy farmer's milking shed and the houses of both farmers. The antenna height is ten metres high and the site operates on mains power. The participants did not indicate whether they had permission or how best to access the site.

Relay R4 was placed near a trig site at an elevation of 407 metres to provide connectivity further down the valley. Relay R4 connects to relay R3 but participants ran out of time before they could finish their plan. The antenna height is ten metres high and the site operates on mains power. The participants did not indicate whether they had permission or how best to access the site.

Relay R5 is also placed near a trig site at an elevation of 420 metres with the intention of providing coverage to Minginui village. Relay R5 is not connected to any other sites but indications are that the participants were looking at connecting it to relay R4. The antenna height is four metres high and the site operates on mains power. The participants did not indicate whether they had permission or how best to access the site.

This discussion shows that the placement and access information has not been well used. Of the five sites, only one site had the best access type selected. None of the sites indicated permission or had notes on placement or access. Also no general information was entered for any of the house sites or the source site. It is possible that if the participants had more time for the planning task, they may have revisited these issues. This indicates that either the participants did not know what they should enter in these fields or that the fields were ignored. Either way, the importance of this information needs to be obvious to the user, and the requested information needs to be more specific than just empty text fields. Also, participants did not seem to consider the power source for any of the relays as they were all set to mains power. It is unlikely that mains power would be available at any of the relay sites, particularly relay R1 and relay R2.

9.3.4 Usability issues

The community representative commented that "WiPlan has a way to go but is a great idea and very useful if it can be refined". Participants found that some of the terminology is too technical and needs to be described using every day language. The community representative described scrolling to find the OK button as his "pet hate". The kaumātua questioned why the window close button was on the left-hand side rather than the right-hand side of the window.

The researcher observed that in the *site adder tool*, participants were confused about the meaning of NZTM and WGS84, and about which one they should use.

Guide and tutorial The school principal pointed out that the overall best strategy was not evident and that the guide should reflect this as some of the wording in the guide was unclear. The sheep and beef farmer mentioned that the tutorial should refer to the legend further and introduce the *site adder tool*. The researcher observed that generated windows such as the *site properties information window* would block the tutorial and guide from view, and that the operator would then have to move the dialog to the right. The animated arrows indicating where sites and links should be created did not appear to be strong enough indicators as the participants struggled at the beginning of the tutorial with placing a house site at the point denoted by the animated arrow. Also, when the tutorial discusses the line-of-sight check box in the *link profile information window*, the tutorial says that the information window has changed but does not explain how. The participants found it difficult to identify what had actually changed in the window.

Link profile dialog The participants had difficulty identifying terrain obstructions on the link profile plot and differentiating terrain obstructions from potential obstructions such as vegetation and buildings. The community representative commented that they did not know the meaning of protocol and why it was there.

Other Participants had difficulty at times distinguishing between the icons for a source, relay and house site. Participants did not notice the zooming and panning buttons or the drop-down list for selecting the map background. The participants found the explore local area feature was confusing and the community representative described it as a “horrible bloody map”.

9.3.5 Expert feedback

The chief technical officer of a local ISP with ten years experience in wireless network planning in rural areas (the wireless network expert introduced in Section 8.3) was asked to comment on the plan designed by the five participants. He commented that the plan was reasonable but that five relays is excessive for an area of that size; he would realistically expect to see a maximum of three solar sites to serve the Te Whāiti valley area. He was pleased that participants identified that placing sites with decent coverage is a good approach. The participants did not consider cost as much as he would like, most likely due to the relay site costing within WiPlan being too low. This indicates that costs within WiPlan should be further investigated in future work to ensure they are realistic. The expert noted that the plan was partially incomplete but said it was clear how the plan would be completed to include Minginui village. The expert stated that the most significant oversight by the participants is that extra sites incur not only building costs but maintenance costs as well, as sites are unreliable. The expert was concerned about the feasibility of the Whakaipu site due to how difficult the site seemed to access. Participants considered the difficulty involved in accessing Whakaipu and elected to use a helicopter. This highlights the issue of cost involved and indicates that in future work, extra cost should be included by WiPlan when a helicopter is used for access.

9.4 Chapter findings

Both trials showed that participants could successfully complete the tutorial and plan feasible wireless networks for their rural area. This section addresses the three questions introduced at the beginning of the chapter as follows.

9.4.1 Did the participants engage in role-playing their personas and collaborate on planning the wireless network?

The study design successfully enabled participants to plan a wireless network for a geographic area about which they had no prior knowledge. The participants were able to engage with their role-playing personas and provide some local knowledge during the planning process. Providing refreshments during the trials helped to create a relaxed and community-like atmosphere. The study design was conservative compared to a real meeting because community members would readily have the local knowledge, whereas in the study design, participants are expected to memorise new information. Therefore the emphasis of the study design is on whether any local knowledge was used during the network planning process. Participants did remember and use this local knowledge, however they found it difficult to memorise local knowledge from their information sheets and plan the wireless network in the short period of time that took place.

In both trials, participants remembered elements of local knowledge and were able to collaboratively apply those elements in certain situations. In the first trial, the participant role-playing the sheep and beef farmer engaged with his persona; he examined the farm map supplied and questioned a wireless link that passed over a shelter-belt on his farm. The community representative also engaged with his persona; he examined the list of trig station locations which the participants explored for placing relay sites. All participants considered their allocated budget for planning the network. In the second trial, the community representative ensured that the village of Minginui was included in the network plan and examined the list of trig station locations which the participants explored for placing relay sites. The dairy farmer noticed that using the Fencepost portal would require an Internet connection at his milking shed to monitor milk levels and so ensured his milking shed was connected to the network. The school principal ensured that the school received a good connection so that they could use video conferencing.

The study design proved to be effective in providing participants with local knowledge and providing a role-playing game to simulate planning a wireless network for a rural community. Participants were able to remember elements of local knowledge from their information sheets and apply those elements in appropriate situations. The study design could be improved by allowing more time for the trials to take place and providing photos or video of the area so participants could see what the terrain and vegetation are like. The trials have shown that middle-aged participants with moderate comfort using computers engage more with their personas and associated information. Providing some sort of incentive for participants to engage more with their personas and associate local knowledge may also help. Real community members have the incentive of an actual wireless network to connect them to the Internet but participants will not have this encouragement. An 'ask the researcher' approach may be an alternative to information sheets for the study design. Rather than trying to remember local knowledge from their information sheets, participants could ask the researcher questions. The research could then determine using some process whether the participant receives an accurate answer, a vague answer or no answer at all.

9.4.2 Did the tutorial assist participants with decision making and troubleshooting during the wireless network planning process?

The tutorial taught participants the wireless networking planning process and introduced them to the tasks that the participants would need to carry out and decisions during the process. The tutorial was successfully completed in both trials, indicating that the tutorial introduces an even amount of information at each step and that the information is described at an appropriate level.

Most of the features introduced during the tutorial were straight-forward and participants understood how each feature was useful. The participants from the first trial quickly applied the process taught by the tutorial and were able to make decisions based on techniques conveyed by the tutorial in the network planning phase. However, participants in the second trial found it difficult to recall the wireless network planning process from the tutorial one they began the network planning phase. This indicates that WiPlan should provide additional planning assistance to users by implementing a wizard or task management support mechanism. It would also be useful for WiPlan to flag issues and guide the participants to address the issue. An example of such an issue would be a network design that is incomplete. Participants in the second trial did remember troubleshooting techniques from the tutorial and were able to use them. The tutorial showed that here is no right or wrong order to execute tasks in wireless network planning, as tasks with dependencies cannot be executed until the dependencies are addressed.

The two main difficulties encountered with the tutorial was with the *explore local area information window* and the *link profile information window*. The *explore local area information window* was considered confusing and difficult to use in both trials. Participants had difficulty understanding the *link profile information window* in trial two as they did not understand the difference between obstructions caused by terrain and obstructions caused by other objects such as trees and buildings. Participants in trial two also seemed to have difficulty deciding whether to pursue line-of-sight by adjusting antenna heights or to simply abandon the link.

The tutorial did help participants with decision making and troubleshooting in both trials. The tutorial could be improved to make it easier for participants to understand. The main issue that participants had was understanding the tutorial wording. Some of the terminology used was too technical and in some cases, the tutorial steps were not verbose enough for participants to gain a full understanding of what that tutorial step accomplished. However the trials have shown that the tutorial does help participants to learn techniques necessary for wireless network planning and help them with decision making.

9.4.3 Were the participants able to plan a wireless network and draw out relevant local knowledge during the process?

The participants successfully planned feasible networks in both trials. Participants created house and relay sites, discussed access, created links, solved line-of-sight issues and computed coverage. Participants successfully planned wireless networks within budget in both trials. The wireless expert was asked which network plan was the more efficient solution and whether they would change it. He chose the wireless network plan from trial one but would change the plan by connecting the houses to a relay rather than to each other. He pointed out that the key to the whole network is the Whakaipu relay site and that he would have to seriously look at access and placement before deciding to place a relay site there. He commented that the Te Whāiti valley is unique in that it is surrounded by national park, thick with vegetation, and poses a difficult wireless network planning problem. He was impressed that in both trials, participants planned a feasible wireless network for the Te Whāiti valley.

WiPlan supported the use of all five strategies for wireless network planning, discussed in Chapter 2. In both trials, participants followed the multi-branch strategy (Section 2.3.5). Participants from the first trial were expected to follow one of the five strategies due to their computer science background. However, it was encouraging that participants from the second trial also followed one of the five strategies and that it was the same strategy that the participants from the first trial used. It is important to note that the participants in the second trial originally started following the guide (the participants from the first trial completely ignored the guide), which steps users through the reverse-branch strategy (Section 2.3.4). However, the participants abandoned the reverse-branch strategy at the first step and naturally followed the multi-branch strategy instead.

Participants were able to draw out some local knowledge but as already mentioned, participants found it difficult to memorise local knowledge from cards and plan a wireless network in short period of time. Local knowledge relevant to site access received the most attention from participants. Participants tended to discuss access to sites but not actually enter that information in to the *site properties information window.* In the first trial, the participants created three relay sites. They entered the best access type for two of the sites; one site was by helicopter and the other by 4WD. The participants entered access notes for one site, explaining that the site could also be accessed via a walking track. This walking track was identified on the community representative's trig station list. In the second trial, participants created five relay sites. They entered the best access for one site as being by helicopter and did not enter any access notes.

Participant consideration of placement issues was poor, though this may have been influenced by not having enough time for planning the network. Also, most of the sites were placed in what participants would consider to be public areas and therefore participants may have thought that placement was not an issue. In the first trial, participants indicated that they had permission to place one of the three sites but did not explain who that permission was from. None of the sites had notes about placement issues. There was little consideration of cultural issues and no consideration of weather conditions. Participants did however consider the power source, electing to use solar power for two of the relay sites and mains power for the other relay site. In the second trial, participants did not indicate permission or enter any placement notes for any of the sites. There was little consideration of cultural issues and no consideration of weather conditions or power source.

Participants in two separate trials successfully created feasible wireless network plans within a given budget. This is a promising result and shows that WiPlan was effective in supporting the planning of a wireless network. Participants from both trials followed the multi-branch strategy for planning their wireless networks which reinforces the success of WiPlan. The participants were able to draw out local knowledge, though not as well as was expected. Solicitation of local knowledge could be improved with minor changes to WiPlan and the study design. Future work should include making the access and placement information that is asked for in the *site properties information window* more specific and making the prompts more forceful for getting the user to enter that information to assist with local knowledge solicitation. Future changes to the study design could include helping with local knowledge solicitation by allowing more time for the participants to plan their wireless network and investigating alternative methods for simulating local knowledge, such as the 'ask the researcher' method explained in Section 9.4.1.

9.4.4 What are the main threats to validity and limitations of the evaluation results?

Though role-playing results have given a strong indication of validity, there is a risk that the role-playing is not wholly representative of end users. However, the roles were well researched and based on real members of rural communities so this risk has been minimised. Local knowledge solicitation is theoretically more difficult in a role-playing scenario than in a real end user scenario because the local knowledge is simulated. In a real end user scenario, the local knowledge already exists (as long as there is a good mix of local community members). Also, end users would have more enthusiasm to achieve their goal of a community network. This is evident by the community involvement in the physically building the CRCnet and Tūhoe community wireless networks.

One limitation of these results is that the performance of WiPlan was not compared to that of another planning tool. Unfortunately, most of the available tools were either too complex to expect end-users to operate or the tools did not support point-to-point wireless network planning (discussed in Chapter 3). A comparison using Radio Mobile is possible as part of future work, though would require the participants to undertake a training session before planning a wireless network. The idea of the training session would be similar to the WiPlan tutorial, though the training session would not be interactive and would be limited in how it assisted the users.

It would have been ideal if the WiPlan user evaluation was conducted using actual people from Te Whāiti. However distance and time constraints (as mentioned in Section 9.1) made this difficult to achieve. It is important to note that the expert rural wireless network planner that evaluated WiPlan and the user study results was the same expert that planned the Te Whāiti network and had good local knowledge of the Te Whāiti area. As mentioned in Chapter 8, it would be interesting to obtain expert reviews from other wireless network planning experts as future work to see if their opinions about WiPlan concur.

9.5 Chapter summary

This chapter explored the influence that WiPlan has on the wireless network planning process. The chapter introduced the study design, describing the importance of role-playing and how role-playing characters based on rural personas is used in the study design. The chapter introduced the Te Whāiti valley that the study design is based on and presented evidence for why the Te Whāiti valley was an appropriate choice. The chapter then presented the findings of the trials; the first with computer science student participants and the second with older non-academic participants who were moderately comfortable using computers. The tutorial was successfully completed in both trials and a complete network was planned in the first trial. The network plan was nearly completed in trial two but the participants ran out of time. Minor issues were identified within WiPlan during the trials. An expert found that both network plans were feasible and that the plan from trial one was preferable. Some threats to validity and limitations of the evaluation results were also addressed.

Overall, the study design proved to be an effective method for evaluating WiPlan. The study design was able to provide participants with local knowledge and use a role-playing game to simulate planning a wireless network for a rural community. Participants engaged in role-playing their personas and collaborated on planning the wireless network. Participants in both trials successfully completed the WiPlan tutorial and used the techniques that they had learned to plan their wireless network with few problems, showing that the tutorial helped to teach users the wireless network planning process. WiPlan successfully assisted participants in both trials to create wireless network plans within a given budget and help those participants with soliciting local knowledge. Suggestions for improving the study design and WiPlan were also mentioned.

Chapter 10

Conclusions

There is a need for broadband Internet in rural areas due to a long history of low telecommunications investment in rural areas of New Zealand. To address this need for rural broadband, point-to-point wireless technology is identified as an appropriate solution for providing broadband Internet to rural areas (Section 1.1). The CRCnet project established that involving the local community in the planning of the wireless network can help reduce planning costs and can bring a number of social benefits to the community.

The CRCnet project established general construction guidelines and used commodity hardware to build six wireless networks, providing inspiration and lessons for this thesis (Section 1.2). Local communities have the best local knowledge of their area including detailed knowledge of the physical environment as well as knowledge about culturally sensitive areas and potential social issues. This leads to the following research question that is asked in the introduction of this thesis:

> Can a software tool be designed to assist members of rural communities with no expertise in wireless network planning, to plan a feasible wireless network?

Wireless network planning is not only complex but involves a broad set of constraints. These include technical, natural and human constraints. The complexity (Section 2.1) and broadness of constraints (Section 2.2) establishes the need for a wireless network planning strategy. Five strategies for wireless network planning are identified (Section 2.3), including associated planning tasks (Section 2.4).

Computer-assisted planning is determined to be an appropriate approach for planning wireless networks in rural areas (Chapter 3). This is because computer-assisted planning can guide rural community members through the wireless network planning process and supports an incremental approach for soliciting constraint information from community members using local knowledge.

To investigate the feasibility of rural communities planning a wireless network, the WiPlan system for wireless network planning was developed. A key issue in wireless network planning is determining the feasibility of a link. WiPlan addresses this issue with a sub-system that hides the complex details from the user. The sub-system is designed such that a user only needs to create a link between two sites and WiPlan will determine whether the link is feasible. Determining the feasibility of a link begins with a radio wave propagation model to determine whether the link is line-of-sight and to estimate the degree of loss that the link will experience.

Evaluation of the eleven most popular radio wave propagation models (Section B) has established that the irregular terrain model and the ITU terrain model are the most suitable models for rural New Zealand due to their support of terrain, frequency and distance. The link profile tool and area profile tool use the irregular terrain model and the ITU terrain model to predict connectivity and coverage respectfully (Section 5.2). Finally, a decision tree was developed that uses the loss and line-of-sight predictions from the link profile tool to present the user with a non-technical explanation of whether the link is feasible (Section 5.2).

A major focus of a wireless network planning system for people with no planning expertise is the user interface design. Personas are used as a basis for designing the user interface of WiPlan. WiPlan is designed around the principles of local knowledge and user support; the design of WiPlan is described in Chapter 6. The WiPlan tutorial introduces the user to key wireless network planning actions and conveys a planning process for users to follow. The WiPlan system is subjected to the same analysis as the existing planning tools described in Section 3.2.1.

A novel evaluation technique, structured as a role-playing game, was developed to explore how WiPlan assists users with planning a wireless network for a rural area (Chapter 9). Two trials took place; the first with computer science student participants (Section 165) and the second with older non-academic participants (Section 9.3). The participants engaged in role-playing their personas and collaborated on planning the wireless network. The trials showed that the tutorial included in WiPlan taught the participants the wireless network planning process, as participants in both trials were able to follow the planning process and execute tasks to plan a rural wireless network.

Some threats to the validity of this evaluation technique were identified in Section 9.4.4. Though role-playing results have given a strong indication of validity, there is a risk that the role-playing is not wholly representative of end users. However, the roles were well researched and based on real members of rural communities so this risk has been minimised.

One limitation of these results is that the performance of WiPlan was not compared to that of another planning tool. Unfortunately, most of the available tools were either too complex to expect end-users to operate or the tools did not support point-to-point wireless network planning (discussed in Chapter 3).

It would have been ideal if the WiPlan user evaluation was conducted using actual people from Te Whāiti. However distance and time constraints (as mentioned in Section 9.1) made this difficult to achieve. It is important to note that the expert rural wireless network planner that evaluated WiPlan and the user study results was the same expert that planned the Te Whāiti network and had good local knowledge of the Te Whāiti area.

WiPlan assisted participants in successfully planning feasible networks in both trials and solicited local knowledge from participants throughout the planning process. Participants created house and relay sites, discussed access, created links, solved line-of-sight issues, computed coverage and were lead by WiPlan to discuss how their local knowledge impacted on site access and placement. Participants successfully planned wireless networks within budget in both trials.

10.1 Research contributions

The research contributions of this thesis include:

- A review of widely-used existing wireless network planning tools, identifying features that a planning tool for use by non-expert rural communities should support, and identification of five strategies for wireless network planning.

- An methodology for identifying natural, human and technical constraints that affect rural wireless network planning. Natural, human and technical constraints were identified in a New Zealand context and the effect of those constraints on rural wireless network planning was analysed.

- A novel HCI study design, structured as a role-playing game, for evaluating cooperative planning software, and a demonstration of its effectiveness for use when the target end users were difficult to attain.

- The proposed software tool was actually built and was fundamental for the aforementioned novel role playing game evaluation.

The primary contribution of this thesis is that the feasibility of designing a wireless networking planning tool, that can assist members of rural communities with no expertise in wireless network planning, to plan a feasible network has been explored and reasonable evidence has been gathered to support the claim that such a planning tool is feasible.

10.2 Future work

The key area of future work would involve an evaluation with real end users working on planning a new wireless network for their local community. Conducting an evaluation with real end users would require improving the cost modeling within Wiplan, as well as refining other aspects in WiPlan. An evaluation with real end users would then provide a benchmark for accurately comparing the role-playing planning approach. WiPlan could also be used with an existing network design to evaluate performance, and compare it to measured performance data if the network actively exists. Refinements and extensions for WiPlan are discussed in this section. Also, two potential avenues for future research are introduced: testing radio wave propagation models and exploring application domains.

10.2.1 WiPlan

Refinements and extensions for WiPlan were identified during evaluation that should be addressed in future work. Vector data support, such as vegetation, roads and buildings, makes it possible for appropriate radio wave propagation models to predict the effect of these objects on radio wave propagation. For example, the effect of vegetation on radio wave propagation could be predicted. The ability to predict loss due to vegetation increases the confidence in whether a given link is feasible.

Further integration of the area profile tool within WiPlan would provide more flexibility for coverage prediction including custom distance ranges and coverage segments. The focus of WiPlan so far has been on point-to-point links and as a result, coverage prediction is currently limited in WiPlan. Further integration would require a user interface window that allowed parameters to be specified for computing a coverage plot. Support for custom distance ranges and coverage segments would assist in the exploration of the rural area for site placement.

Algorithmic planning support and integration of network analysis techniques would assist in the technical design of wireless network plans. Minimum antenna height calculation support in WiPlan when establishing links would provide further information to the user about the cost and feasibility of a link. Automatic frequency planning for optimally assigning radio channels to links in the network would help to minimise potential interference for the wireless network plan. Providing analysis support would be a major step forward for WiPlan. Such analysis includes: predicting interference within the network and from other sources; network capacity; and network reliability. The ability to perform this analysis on a wireless network plan would help to validate the technical performance of the plan.

The wider network planning process around WiPlan could be further explored to determine how a community gets to the point of using WiPlan to plan a wireless network and what happens afterward. For example:

- Identifying methods of making rural communities aware that they could plan their own wireless network to provide broadband Internet.
- Establishing how interested members of the rural community become involved in a community network project.
- Making WiPlan available for the community to obtain.
- Establishing a procedure for how network planning meetings should operate including information about how many hours the community should spend on the project.
- Identifying the methods of planning advice available to the community.
- Describing a procedure for how a wireless network plan is verified by a wireless network planning expert.
- Establishing a procedure for finalising a wireless network plan and arranging with the expert for the network to be built.

10.2.2 Testing radio wave propagation models

WiPlan could be used as a testbed for developing and testing radio wave propagation models. A corpus of real-world wireless network plans with associated measurement data would allow wireless network plans to be selected for testing in WiPlan. For example, the corpus could contain a network plan for the Tūhoe network (Section 1.2.1.2). This network plan would contain all of the sites and links that make up the Tūhoe network. Each link of the Tūhoe network would have a set of measurement data associated with it. The measurement data would include key performance data, such as measured loss, over a suitable time period. Radio wave propagation models could be modularised such that models could be swapped in and out of WiPlan. This would allow the loss, and possibly other factors, to be predicted by these radio wave propagation models which could then be compared to the real-world measurements. Effects due to distance and terrain are supported by WiPlan. The addition of vector data support to WiPlan would allow models that address objects other than terrain, such as vegetation and buildings, to be developed and tested.

10.2.3 Exploring application context

The application context of cooperative community planning could be explored. WiPlan has established that a community of people can plan a feasible wireless network for a rural area in New Zealand. Therefore it is conceivable that other types of communities could also plan a wireless network for their given context.

One example of a different application context would be planning a wireless network within an apartment building. Residents of the apartment building could work together to plan a wireless network to provide Internet connectivity to every resident. WiPlan could assist these residents with planning this apartment network. WiPlan would require vector support and radio wave propagation models for predicting loss due to building materials. The importance of the constraints involved may change to compared to their importance in rural areas. For example, most natural features would be irrelevant in an apartment building. New constraints may need to be considered and as a result, other local knowledge may be required. Social and cultural constraints may be more prominent in an apartment building than in rural areas due to potential diversity of cultures and high density of people. Parts of an apartment building may be communal, such as a community centre or religious meeting place. This could introduce further cultural and social constraints that would not have an affect in the rural context.

Another example of a different application context would be investigating a rural setting outside of New Zealand that has different constraints and requirements for local knowledge. Such a setting could be the Australian outback where large areas of the terrain are almost completely flat and the population density is approximately 1 person per 100 square kilometres. An interesting constraint is that Ayers Rock and Kata Tjuta, the major areas of elevated terrain in the central outback, are sacred in the Aboriginal culture. Another setting could be tropical islands such as Samoa where vegetation is lush and the wireless network would need to connect multiple islands together. Most of Samoa's villages are located close to the coast on both islands and are surrounded by lush tropical vegetation. Adding support for predicting how radio wave propagation is affected by tropical vegetation and the ocean to WiPlan would make it possible to plan a feasible wireless network for Samoa. Rural settings in other parts of the world have their own social and cultural constraints that will need to be addressed as part of the wireless network planning process.

Appendix A

Existing CAP tool evaluation

The existing tools were compared to determine whether there was support for incorporating local knowledge in the wireless network plan and how the tool helped the user in the planning process. There are twelve existing tools that were considered. This is not an exhaustive list of tools but these twelve were found to be prominent tools for wireless network planning. Tools will be referenced by name and allocated letter in the following discussion.

A Aircom International Connect [1] is a commercial CAP tool, screen shots indicate that it is for Windows.

B Mentum Planet [9] is a commercial CAP tool for Windows.

C ComSiteDesign [2] is a commercial CAP tool for Windows.

D The command-line Digital Line-of-Sight CAP tool for DOS 2.0 that is detailed in a report released by the US Department of Commerce in 1989 [68]. Though designed for "persons having no experience in programming", the program was intended for use by wireless system engineers. The Digital Line-of-Sight tool will be referred to as the DLOS tool in the following discussion.

E EDX SignalPro [4] is a commercial CAP tool, screen shots indicate that it is for Windows.

F Forsk Atoll [6] is a commercial CAP tool for Windows.

G Google Earth [8] is a virtual globe program for Windows, Linux and Mac that allows the user to explore the earth in a 3D environment. Though not actually a CAP tool, Google Earth is popular for wireless network planning as it is freely available and has useful features including: terrain elevation, satellite imagery, 3D visualisation, distance measuring tools, image overlay and elevation profile between two points.

H Overture Online [14] is a commercial CAP tool for Windows.

I Radio Mobile [18] is a Freeware CAP tool for Windows.

J Pathloss [15] is a commercial CAP tool for Windows.

K SPLAT! [20] is an Open Source CAP tool for Linux/Unix.

L WiTech [25] is a commercial Web-based CAP tool.

A.1 Local knowledge and user support

Five tools had features that could be used for incorporating local knowledge. EDX SignalPro (E) provides a building editor module that allows the user to import and edit building plans. This may be useful for planning indoor wireless networks or for modeling accurate building heights. DLOS (D) and Pathloss (J) allow obstacles such as trees and water to be added manually. In SPLAT! (K), the maximum height of ground clutter can be specified by the user so the clutter height is considered in further analysis.

Overture Online (H) allows the use to create custom flags for a site to store specific meta data. For example, the user could create a flag for storing the owner of the site. Overture Online also allows the user to reject a site from consideration and select a reason from a set list. This list includes the options of access limitations and inappropriate location but does not support the specification of the details.

Six tools had features that help the user during the planning process, mainly as documentation.

EDX SignalPro (E) has a project wizard that allows the user to “rapidly set up a project from a selection of system-specific templates” and will “instantly display a map view with relevant GIS data for your chosen area, which can be selected by simply entering a city name”. It is unclear how the user is supported during the rest of the planning process.

Overture Online (H) includes a six-step tutorial in the side bar to help the user and has integrated help. Overture Online also has extensive online documentation, as does Pathloss (J). DLOS (D) and SPLAT! (K) have extensive usage reports. Mentum Planet (B) has an online knowledge base for user support.

Most tools seem to have the reasonable expectation that the user already knows the planning process, as the majority of these tools are for the expert planner.

A.2 Algorithmic planning support

EDX SignalPro (E) is the most featured tool in terms of optimisation methods including support for antenna height optimisation, cell site/AP layout optimisation, automatic power control (APC) and automatic frequency planning (AFP) using simulated annealing.

Antenna height optimisation is the most common optimisation method among the existing tools. Eight of the twelve tools state support for antenna height optimisation including: Mentum Planet (B), ComSiteDesign (C), DLOS (D), EDX SignalPro (E), Forsk Atoll (F), Overture Online (H), Pathloss (J) and SPLAT! (K).

Six of the twelve tools provide some level of support for cell site/AP layout optimisation including: Aircom International Connect (A), Mentum Planet (B), ComSiteDesign (C), EDX SignalPro (E), Overture Online (H) and Radio Mobile (I).

Six of the twelve tools have support for automatic frequency planning which is optimally assigning radio channels such that any interference is minimised. The tools are: Aircom International Connect (A), Mentum Planet (B), ComSiteDesign (C), EDX SignalPro (E), Forsk Atoll (F) and Overture Online (H).

Four of the twelve tools have support for automatic power control which is optimally assigning power levels to each transmitter. The tools are Aircom International Connect (A), EDX SignalPro (E), Forsk Atoll (F) and Overture Online (H).

A.3 Computer assistance

There are several ways that a wireless network tool can provide computer assistance. This section describes how geographic support and analysis support are featured in the twelve existing tools.

A.3.1 Geographic support

Google Earth (G) is the most featured tool in terms of geographic support. The entire earth is mapped using satellite imagery and aerial photography over 3D terrain and provides a wealth of geographic data layers such as transport, towns/cities and country/state borders. Layers such as 3D buildings and key geographic features are also available for particular areas in the world, particularly the United States. Overture Online (H) is similarly featured but restricted to 2D maps with 3D visualisations.

All of the evaluated tools with a graphical user interface[1] provide support for a variety of map types including shaded terrain, aerial photos and street maps. These tools also support the use of various geographic databases such as terrain, transport, population statistics and building heights. Seven of the tools evaluated provide the ability for 3D visualisation of network designs; Radio Mobile does not currently provide a 3D visualisation.

All of the tools except for DLOS (D) provide GIS integration and/or export functionality. Mentum Planet (B) and Forsk Atoll (F) provide MapInfo GIS integration. Overture Online (H) embeds Bing maps, which is Microsoft's mapping service, and ComSiteDesign (C) provides ArcView GIS integration. The other tools can export to formats such as shapefiles and KML as used by Google Earth.

Navigational aids for mapping should include scale and orientation, as well as the ability to pan and zoom around the map. Five of the tools provide a scale. Google Earth (G) and Overture Online (H) are the only tools that explicitly show orientation. Eight of the ten remaining tools imply that up is north. All of the evaluated tools provided panning and zooming ability with the exception of DLOS (D), Radio Mobile (I), SPLAT! (K) and WiTech (L).

A.3.2 Analysis support

Path profile analysis and coverage analysis are fundamental to wireless network planning. Nine tools support path profile analysis. Google Earth (G) is capable of providing an elevation profile while WiTech (L) and Overture Online (H) did not currently have support for path profile analysis. Ten tools support coverage analysis; DLOS (D) and Google Earth (G) were the two tools that did not support coverage analysis. Google Earth (G) can however display

[1] Tools that do not have a graphical user interface include DLOS (D), SPLAT! (K) and WiTech (L).

image overlays meaning that a coverage plot generated by another tool can be displayed in Google Earth.

Other forms of analysis include traffic loading, interference, capacity and reliability. Five of the twelve tools support traffic loading analysis: Aircom International Connect (A), Mentum Planet (B), ComSiteDesign (C), EDX SignalPro (E) and Forsk Atoll (F). Eight tools support interference analysis: Aircom International Connect (A), Mentum Planet (B), ComSiteDesign (C), EDX SignalPro (E), Forsk Atoll (F), Overture Online (H), Radio Mobile (I) and Pathloss (J).

Capacity analysis is supported by six of the twelve tools: Aircom International Connect (A), Mentum Planet (B), ComSiteDesign (C), EDX SignalPro (E), Forsk Atoll (F) and WiTech (L). Nine of the twelve tools have support for reliability analysis varying from support for propagation loss prediction through to worst month analysis [30, 33]. These nine tools include Aircom International Connect (A), Mentum Planet (B), ComSiteDesign (C), DLOS (D), EDX SignalPro (E), Forsk Atoll (F), Radio Mobile (I), Pathloss (J) and SPLAT! (K).

A.4 Wireless network planning action support

Six of the twelve tools were compared based on five main actions necessary for wireless network planning. These actions are the creation of a site (A1), naming of a site (A2), setting/adjusting antenna heights (A3), conducting a point-to-point analysis (A4) and conducting a point-to-multipoint analysis (A5). Google Earth (G), Radio Mobile (I) and Splat! (K) are freeware and hence could be evaluated by using the actual tools. A trial of Overture Online (H) was obtained which allowed evaluation by actual use. Detailed documentation was used to evaluate DLOS (D) and Pathloss (J).

A.4.1 Creating a site (A1)

Overture Online (H) allows creation of a site by right-clicking on the map where the site is to be placed and selecting *Add Site Here*. Google Earth (G) is similar but requires the user to left-click *Add Placemark* on the toolbar and drag the placemark to where the site should be placed. Alternatively the latitude and longitude can be entered if they are known. The user then left-clicks *OK*. DLOS (D) allows the entry of geometric coordinates for the transmitting and receiving sites as well as the elevation at that point (including tower height if applicable) in the *Earth geometry* module.

To create a site in Pathloss (J), the user left-clicks the *Site list* button on the toolbar to open the *Site list* window. The site name, latitude and longitude can then be entered in the table. The map will show the sites when the *Site list* window is closed. Sites can also be imported from a CSV file or any delimited text file.

Splat! (K) requires a text file with specific contents to create a site. The text file must contain the name, latitude, longitude and antenna height where a newline is used as a separator. To create a site in Radio Mobile (I), the user right-clicks on the map where the site should go to position the map cursor and then left-click *Units properties* on the toolbar to open the *Units properties* window. The user selects an unallocated unit from the list and left-clicks *Place unit at cursor position* or manually enters the latitude and longitude, then left-clicks *OK*.

Creating a site is a fundamental action in wireless network planning and therefore needs to simple and straight-forward to carry out. Overture Online (H) and Google Earth (G) meet this criteria.

A.4.2 Naming a site (A2)

To name a site in Overture Online (H), the user left-clicks the particular site once to select the site, and a second time to show the site properties in the sidebar. The site name can then be edited. In Google Earth (G), the user right-clicks the placemark to be named and left-clicks *Properties*. The name can then be entered and the user left-clicks *OK*. In the DLOS program, site names are entered when creating a link using the *Select a link* module.

To change the name of a site in Pathloss (J), the user left-clicks the *Site list* button on the toolbar to open the *Site list* window. The user enters the new site name in the table and when the *Site list* window is closed the site will have the new name. Splat! (K) requires the site name to be specified in the site text file, as explained for site creation. In Radio Mobile (I), a site can be named by left-clicking *Units properties* on the toolbar and selecting the appropriate unit. The user can edit the name and then left-click *OK*.

A.4.3 Selecting heights (A3)

Selecting heights in Overture Online (H) is similar to naming a site. The user left-clicks the particular site once to select the site, and a second time to show the site properties in the sidebar. The structure height above ground can then be edited. Selecting heights in Google Earth (G) is also similar to the procedure for naming a site. The user right-clicks the placemark to be named and left-clicks *Properties*. The user then left-clicks the *Altitude* tab and can enter the altitude for the site. It is important to note that altitude is not the same as antenna height. The user then left-clicks *OK*.

DLOS (D) determines heights using the *Primary antenna height recommendations* module. Both antenna heights can be calculated or if one antenna height is known, then the other can be determined using the module. Pathloss (J) requires that a point-to-point profile has been generated before antenna heights can be calculated. Once the profile has been generated, antenna heights can be calculated by left-clicking *Design* and selecting *Antenna heights* in the file menu to enter the antenna heights module. The user then left-clicks the calculate button to calculate the antenna heights.

Splat! (K) requires the site's antenna height to be specified in the site text file, as explained for site creation. Radio Mobile (I) allows the site elevation to be edited via *Units properties* but true antenna height adjustment occurs during point-to-point analysis.

A.4.4 Point-to-point analysis (A4)

Overture Online (H) and Google Earth (G) do not support point-to-point analysis, though point-to-point analysis is in active development for Overture Online (H) and Google Earth (G) has a elevation profile feature. Splat! (K) allows point-to-point analysis using the following command-line arguments

```
splat -t tx_site.qth -r rx_site.qth -p terrain_profile.png
```

where tx_site.qth is the transmitter text file and rx_site.qth is the receiver text file.

Point-to-point analysis can be conducted in Radio Mobile (I) in the following way. The user should left-click *Tools* on the file menu and select *Radio Link*. The user can then select the transmitter site and receiver site from drop-down lists. Antenna heights and frequency can be entered and require the *Apply* button to be clicked in order for the new values to be considered in the analysis. Figure A.1 shows an example of point-to-point analysis in Radio Mobile (I).

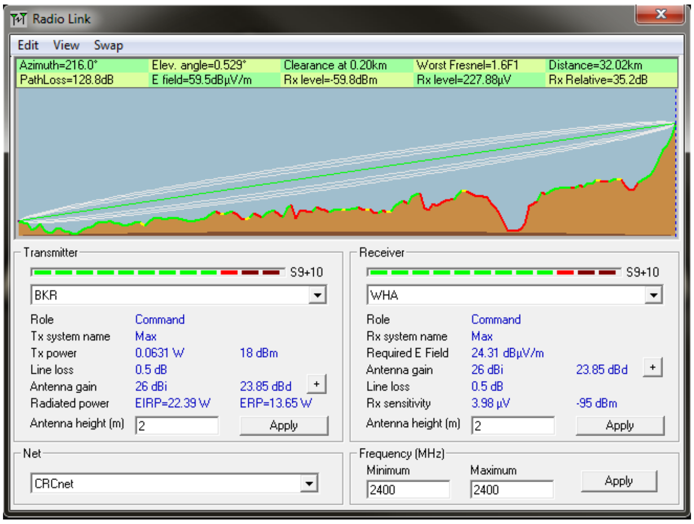


Figure A.1: Radio Mobile Link Profile

In Pathloss (J), point-to-point analysis is initiated by selecting the *Point to point link* cursor from the toolbar. The user left-clicks on one of the sites and drags to the other site to create the link. The user can then left-click on the link and select terrain data from the pop-up menu to open the terrain data module. The user can then left-click *Operations* and select *Generate Profile* on the file menu to generate the elevation profile.

Point-to-point analysis in DLOS (D) requires stepping through several modules in a set order. The user creates a link using the *Select a link* module and enters information such as names and site designator codes. The link is allocated an eight letter name by joining the transmitter and receiver designator codes together. The link can now be selected by entering the link name. The user then enters geometric coordinates for the two sites using the *Earth geometry* module. Clutter information can be entered using the *Path profile and effective earth radius* module and antenna heights can then be calculated using the *Primary antenna height recommendations* module. The *Path profile and ray traces* module can then be used to plot a path profile. Subsequent modules may require additional input before the *Digital link design summary* module can be used to determine link performance.

A.4.5 Point-to-multipoint analysis (A5)

Google Earth (G) and DLOS (D) do not support point-to-multipoint analysis. Pathloss (J) supports point-to-multipoint analysis but the instructions for doing so are not documented. Point-to-multipoint analysis can be conducted in Overture Online (H) by left-clicking *Layers* and double-left-clicking *Serving Site* to compute coverage for all sites. Coverage can be computed in Splat! (K) with the following command-line arguments

```
splat -t tx_site.qth -c receiver_height -o tx_coverage.png
```

where tx_site is the transmitter text file, receiver height is in feet and tx_coverage.png is the image file where the coverage plot is drawn. Figure A.2 shows an example of a coverage plot in Splat! (K).

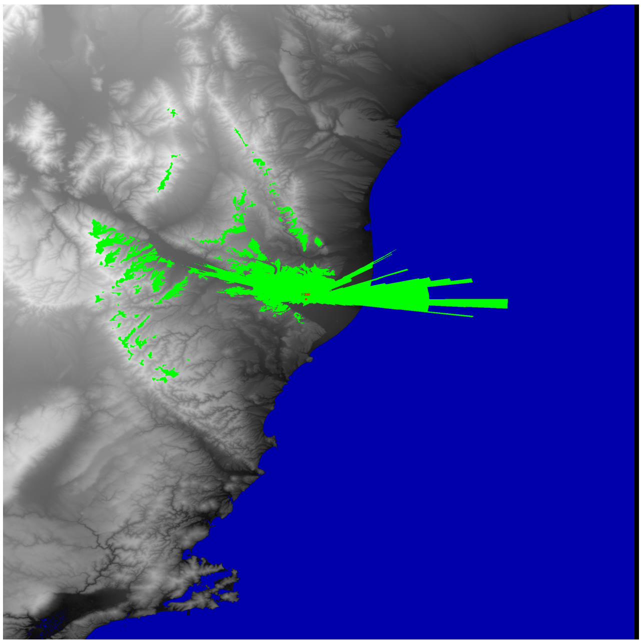


Figure A.2: Splat! coverage plot

Coverage is computed in Radio Mobile (I) by left-clicking *Tools* on the file menu, selecting *Radio coverage* and left-clicking *Single Polar*. The user then selects the centre transmitting unit and the mobile receiving unit from drop-down lists. The range of the coverage plot can be specified as well as some additional parameters. Clicking *Draw* will compute the coverage and display the coverage plot on the map.

A.4.6 Action conclusions

These five actions are fundamental for wireless network planning and therefore need to be simple and straight-forward to carry out for non-experts from rural communities. Comparing how these actions are implemented in the six tools (DLOS (D), Google Earth (G), Overture Online (H), Radio Mobile (I), Pathloss (J) and Splat! (K)) has identified how each action for each tool meets or does not meet this criteria. DLOS (D) and Splat! (K) do not meet this criteria as non-experts from rural communities are not expected to be comfortable with the command-line.

A1 Overture Online (H) and Google Earth (G) provided simple and straight-forward implementations for placing a site, though Overture Online (H) had the most appropriate implementation.

A2 All of the tools provided simple and straight-forward implementations for naming a site, again Overture Online (H) had the most appropriate implementation.

A3 Overture Online (H) and Radio Mobile (I) provided simple and straight-forward implementations for selecting height.

A4 Radio Mobile (I) and Pathloss (J) provided simple and straight-forward implementations for point-to-point analysis.

A5 Overture Online (H) and Radio Mobile (I) provided simple and straight-forward implementations for point-to-multipoint analysis.

These results show that for simple and straight-forward action implementation, Overture Online (H) is the most appropriate tool. Unfortunately Overture Online (H) does not implement the point-to-point analysis action which is fundamental for wireless network planning in rural areas.

Appendix B

Radio wave propagation models

Propagation models provide the ability to predict the expected loss that a wireless link might experience. Propagation models can be categorised as general models, foliage models, urban models and terrain models. Discussion of these models is restricted to those models that are suitable for outdoor areas. Rain attenuation models are not discussed as the frequencies expected to be used for planning rural wireless networks are not typically affected by rainfall. Table B.1 shows a summary of the models that are discussed and some of the key features that are considered when selecting a model to use.

B.1 Free-space

Free-space is a common term in the following discussion and therefore requires some explanation. Free-space is defined as a space that contains no particles and no fields of force. Formally it is distinguished from a vacuum, which contains no particles but may contain fields [60].

B.2 Free-space models

This section discusses three models for radio wave propagation that are based on free-space.

Model name	Model type	Frequency range	Tx height	Rx Height	Distance/depth	Terrain data	Reference
Free-space	General					No	[27, 111]
Friis equation	General					No	[72]
Two-ray	General	300 MHz - 300 GHz				No	[?, 109]
Weissberger's	Foliage	230 MHz - 95 GHz			400 m	No	[123]
ITU foliage	Foliage	30 MHz - 30 GHz				No	[34]
Okumura	Urban					No	[105]
Hata	Urban	150 - 1500 MHz	30 - 200 m	1 - 10 m	1 - 20 km	No	[80]
Hata-Davidson	Urban					No	[52]
Egli	Terrain	40 MHz - 1 GHz				No	[65]
Longley-Rice	Terrain	20 MHz - 20 GHz	0.5 - 3000 m	0.5 - 3000 m	1 - 2000 km	Yes	[82, 83, 94]
ITU terrain	Terrain					No	[33]

Table B.1: A selection of radio wave propagation models and key properties.

B.2.1 Free-space path loss model

The free-space path loss (FSPL) model [27, 111] determines the loss in signal strength that a radio wave would experience from an unobstructed line-of-sight path through free space, known as *free-space basic transmission loss*.

Free-space path loss is proportional to both the distance squared and frequency squared, as shown in Equation B.1.

$$L_{bf} = \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi df}{c}\right)^2 \; dB \tag{B.1}$$

In Equation B.1, λ is wavelength (in metres), f is frequency (in hertz), d is the distance from the transmitter (in metres) and c is the speed of light through air (~2.998×10^8 *metres/second*). The free-space model is not valid for small distances as the spreading out of electromagnetic energy in free-space is determined by the inverse square law and hence as $d \to 0$, the received power becomes greater than the transmitted power. Free-space path loss is the ratio $\frac{p_t}{p_r}$ where p_t is the transmitter power and p_r is the received power. It is convenient to express free-space path loss in dB with frequency in MHz and distances in km. The FSPL equation can also be expressed in logarithm form as Equation B.2.

$$L_{bf} = 20\log_{10}(d) + 20\log_{10}(f) + 32.45 \; dB \tag{B.2}$$

B.2.2 Friis transmission equation

The Friis transmission equation, derived by Harald T. Friis [72], calculates the *transmission loss* of a radio link in free-space. The ratio of power received (P_a) to power transmitted (P_t) is given in Equation B.3.

$$\frac{P_a}{P_t} = A_r A_t / d^2 \lambda^2 \tag{B.3}$$

In Equation B.3, At and Ar are the effective area of the transmitting and receiving antennas, respectively, λ is the wavelength, and d is the distance.

The units for effective areas, wavelength and distance must be the same. By substituting At and Ar in Equation B.3 with Equation B.4 (where G is the gain of the respective antenna in dBi), then Equation B.5 can be derived which uses antenna gains rather than effective areas.

$$A_{eff} = \frac{\lambda^2}{4\pi} G \tag{B.4}$$

$$\frac{Pr}{Pt} = G_T G_R \left(\frac{\lambda}{4\pi R} \right)^2 \tag{B.5}$$

The antennas are assumed to be in free-space with no multipath and correctly aligned and polarized. Empirical adjustments can accommodate effects such as absorption loss and the misalignment and polarization of antennas.

B.2.3 Plane-earth two-ray reflection model

The plane-earth two-ray reflection model [46] calculates *ray path transmission loss*, expanding on the FSPL model by introducing a single ground reflection. It is useful for short radio paths around 10 km in length where the earth's curvature can be ignored. In situations where low antennas are used and the terrain is uncluttered, it can be assumed that ground reflection will occur at grazing incidence, meaning that the reflected signal will almost be parallel with the ground. Figure B.1 shows an example of such a situation. A useful approximation for these situations is the two-ray model with a reflection coefficient of -1. The direct (s_1) and reflected (s_2) rays are calculated using Equation B.6 and Equation B.7 respectively, where d is the horizontal distance and h_1 and h_2 are the heights of the antennas above ground, all in the same units.

$$s_1 = \sqrt{d^2 + (h_1 - h_2)^2} \tag{B.6}$$

$$s_2 = \sqrt{d^2 + (h_1 + h_2)^2} \tag{B.7}$$

The resulting field strength (e) can then be calculated in complex notation

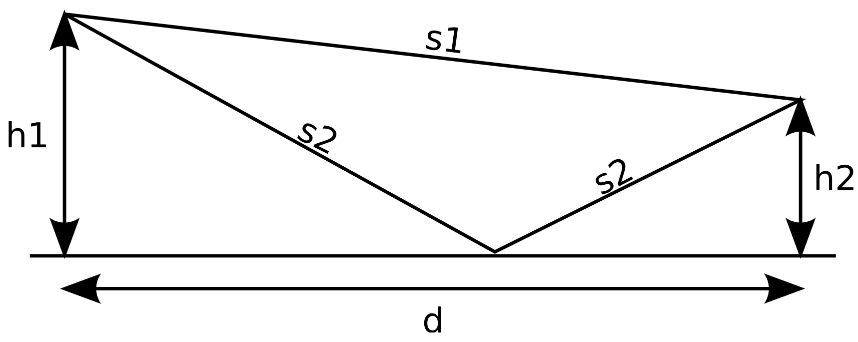


Figure B.1: The two-ray model applied to a particular link.

using Equation B.8 where A is a normalising constant and ρ is the complex reflection coefficient of the ground with an approximate value of -1.

$$e = A \left\{ \frac{\exp\left(-jks_1\right)}{s_1} + \rho \frac{\exp\left(-jks_2\right)}{s_2} \right\} \; dB\mu V/m \tag{B.8}$$

The ground reflection is assumed to be of a signal strength close to that of the direct path signal. The receiving antenna sees a direct path signal followed by a slightly delayed ground-reflected ray; as a consequence, the two rays may be in phase and add constructively, or be out of phase and add destructively. By applying the equations in Appendix C, it is possible to determine ray path transmission loss from the field strength (e) calculated in Equation B.8.

B.3 Vegetation models

This section discusses two popular models for predicting radio wave propagation with respect to vegetation.

B.3.1 Weissberger

Weissberger's modified exponential decay model [123] is a radio wave propagation model for estimating path loss for a link when one or more trees lie between the transmitter and the receiver, as shown in Figure B.2. The model is designed for situations where the line-of-sight path is blocked by dense, dry and leafy trees. The model was formulated in 1982 and is valid for frequencies from 230 MHz to 95 GHz and foliage up to 400m in depth. Only the *loss rela-*

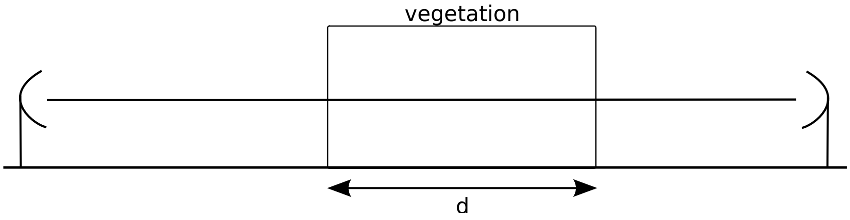


Figure B.2: Model of a link with vegetation obstruction.

tive to free space (L_m) due to vegetation is calculated; path loss computation requires the additional calculation of free-space loss. The Weissberger model is calculated using Equation B.9, where L_m is the loss due to foliage in dB, f is the transmission frequency in GHz and d is the distance that the radio wave travels within the vegetation in metres.

$$L_m = \begin{cases} 1.33 f^{0.284} d^{0.588} & if\ 0 < d \leq 400 \\ 0.45 f^{0.284} d & if\ 0 < d \leq 14 \end{cases} \tag{B.9}$$

B.3.2 ITU Model

The ITU define two models for propagation modelling in vegetation [34]. The ITU Terrestrial Model for One Terminal in Woodland is for a radio path where one end of the path is within woodland or similar extensive vegetation, as shown in Figure B.3. The additional loss due to vegetation can be characterized by the specific attenuation rate (dB/m) due primarily to scattering, and the maximum additional attenuation due to diffraction and absorption. The *loss relative to free-space* (L_m) due to vegetation is calculated using Equation B.10, where d is the length of the path in metres, Υ is the specific attenuation in dB/m and A_m is the maximum attenuation for one terminal within a specific type and depth of vegetation in dB.

$$L_m = A_m \left[1 - \exp\left(-d\Upsilon / A_m\right)\right] \tag{B.10}$$

The *loss relative to free-space*, L_m, is in addition to all other forms of loss including, for example, free-space and diffraction loss. The value of Υ dB/m depends on the species and density of the vegetation. Approximate values of Υ as a function of frequency are available in the ITU Recommendation [34].

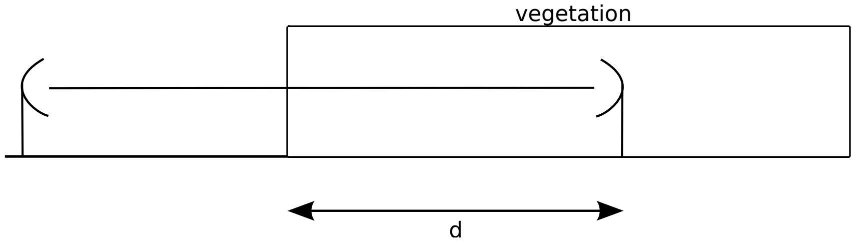


Figure B.3: Model of a link with one terminal in vegetation.

The ITU Single Vegetative Obstruction Model addresses the situation where the radio path is obstructed by a single vegetative obstruction where both the transmitter and receiver are outside the vegetation, as shown in Figure B.2. The model differs depending on whether the frequency is above or below 1 GHz. For the latter, the equation simply incorporates the specific attenuation, the distance that the radio wave travels within the vegetative canopy and a maximum limit, shown in Equation B.11 where, d is the distance that the radio wave travels within the vegetative canopy in metres, γ is the specific attenuation in dB/m and $L_m \leq$ lowest excess attenuation for other paths. This maximum restriction is necessary as if the specific attenuation is sufficiently high, then a lower-loss path will exist around the vegetation.

$$L_m = d\Upsilon \ dB \tag{B.11}$$

When the frequency is above 1 GHz, diffraction over and around the vegetation, the ground reflected component and scattering through the vegetation itself must all be calculated. These components are then summed to give the total loss. These calculations are much more complex than other calculations described in this chapter and therefore will be omitted. Details of the calculations involved are in the ITU Recommendation [34].

B.4 Urban city models

The following urban city models predict *ray path transmission loss:*

The Okumura model [105] was first described by Yoshihisa Okumura in 1968 and is based on measurements at various frequencies in urban Japan. The model is valid for distances between 1 and 100 km. The measured values were statistically analysed to determine median field strengths and derive numerous correction factors. These factors included adjustments for urbanness, terrain slope, roughness and receiver location relative to nearby hills, valleys and localised obstructions. The model is urban focused and is in the context of Japanese cities, Tokyo in particular. There are three variants of the model for use in urban, suburban and open areas. The typical US suburban situation is considered to be somewhere between Okumura's suburban and open areas. The application of Okumura's model involves the use of numerous curves (primarily based on Okumura's empirical field strength data) to determine adjustment factors to be applied to field strength.

In 1980, Masaharu Hata [80] simplified the Okumura model by restricting the distance to less than 20 km and frequency to less than 1500 MHz . Hata's model is designed for predicting the behaviour of cellular transmissions in built up areas and to Okumura's model adds the effects of diffraction, reflection and scattering caused by city structures. However the model ignores the terrain between the transmitter and receiver as the model assumes that the transmitter would normally be located on hills.

As with the Okumura model, there are three variants of the model for use in urban, suburban and open areas. The urban variant is for use in a built-up city to large town where buildings and houses exceed two storeys, or large villages with houses close together and tall, dense trees. The suburban variant is for areas scattered with trees and buildings and the open variant is for open areas where there are no tall trees or buildings, such as farmland. [112]

In 1997, David Brown and Gregory M. Stone added an extension to Hata's work, known as the Hata/Davidson model [52]. Brown and Stone included frequency and distance corrections to extend the limitations on Hata, particularly the distance range to 300km and frequency to between 1500 and 2000 MHz. Corrections are also included for antenna heights. Under some conditions, the model can yield losses less than that calculated by the free-space model. In these cases, the free-space value should be used.

B.5 Terrain models

This section describes three radio wave propagation models that consider the effects of terrain in their predictions.

B.5.1 Egli Model

John Egli derived a propagation model that calculates the *transmission loss* in 1957 for frequencies between 40 MHz and 1 GHz [65]. Egli predicts the median path loss based on real-world data from UHF and VHF television transmissions in several large cities. The model assumes gently rolling terrain with average hill heights of approximately 15 metres . The model can be applied to scenarios involving irregular terrain however, at short range, the model loses accuracy. The free-space propagation model is more accurate for these short distances. Equation B.12 shows the Egli model where L is the median loss, d is the path distance and β is $\left(\frac{40}{f}\right)^2$ (where f is in MHz). G_b and G_m are the gains of the base antenna and mobile antenna respectively. h_b and h_m are the heights of the base antenna and mobile antenna respectively.

$$L = G_b G_m \left[\frac{h_b h_m}{d^2}\right]^2 \beta \; dB \tag{B.12}$$

B.5.2 Irregular terrain model

The Irregular Terrain Model (ITM) [82, 83] is used for calculating the *ray path transmission loss* for links in the frequency range of 20 MHz to 20 GHz and distances between 1 km and 2000 km. The ITM was first published in 1965 as the Longley-Rice model and then revised in 1966 and 1967 [111]. The model was implemented as a computer program in 1968 [94] and further developed to produce the ITM during the 1970s. The model was initially created for the needs of frequency planning in television broadcasting in 1960s America and was extensively used for preparing the tables of channel allocations for VHF/UHF broadcasting.

The Longley-Rice model has two parts: a model for predictions over an area and a model for point-to-point link predictions. The model predicts long-term median propagation loss over irregular terrain. Input parameters include environmental information such as climate, surface refractivity, effective radius of the earth, ground conductivity and permittivity. The user can specify antenna heights, polarisation and variability confidence values in terms of time, location and situation. The complex computer method computes predicted loss based on these parameters by considering effects from such phenomena as diffraction and scattering.

B.5.3 ITU Terrain Model

The ITU Terrain model [33] calculates the *ray path transmission loss* by predicting the median path loss based on diffraction theory. The model determines path loss based on diffraction caused by the highest obstruction in the path. The model is calculated using Equation B.13 where A_d is the diffraction loss and h is the height difference in metres between the highest obstruction and the path's line-of-sight trajectory (h can be negative). F_1 is the radius of the first Fresnel ellipsoid which is calculating using Equation B.14, where f is the frequency in GHz, d is the path length in kilometres and d_1 and d_2 are distance from the highest obstruction to the transmitter and receiver respectively. Equation B.13 is deemed valid for losses over 15 dB.

$$L_t = \frac{-20h}{F_1}\ dB \tag{B.13}$$

$$F_1 = 17.3\sqrt{\frac{d_1 d_2}{fd}} \tag{B.14}$$

Appendix C

Converting field strength to loss

In order to convert a field strength (e) in $dB\mu V/m$ to a loss in dB, it is necessary to follow these steps.

1. Determine the antenna factor (AF) using Equation C.1 where f is the frequency in MHz and G is the antenna gain in dBi.

2. Calculate voltage (V_o) using Equation C.2

3. Calculate the dBm equivalent of V_o using Equation C.3

$$AF = 20 \times \log f - G - 29.78 \tag{C.1}$$

$$V_o = e - AF \tag{C.2}$$

$$V_o(dBm) = V_o - 107 \tag{C.3}$$

Appendix D

Personas

D.1 Sheep and beef farmer

You are a 53 year old sheep and beef farmer that has been farming for 30 years. You work dawn til dusk on the farm most days and when you can, enjoy a spot of hunting and brewing beer. You are married with three children - two daughters and a son. The eldest daughter is working in London and it would be great to video Skype and share photos with her - the current dialup cuts out and makes audio Skyping worse than a phone call, and emails with a single photo takes minutes to download. Though you won't touch a computer, your spouse is quite clued up and is keen to do Internet banking and some online selling of your wool and beef (they manage the books). It would also be great to get long-range weather forecasts. Your teenage son enjoys playing computer games and keeps reminding you how he wants to be able to play online. He and your youngest daughter also frequently talk about Facebook and how it is so slow on dialup.

- Lambing is during August-September. At this time you want people well away from the ewes and their lambs.
- There are a number of bulls and rams on your farm. Some are prone to misbehaving and may confront and even charge a unwary person.
- Figure D.1 shows the map of the farm that was supplied showing the

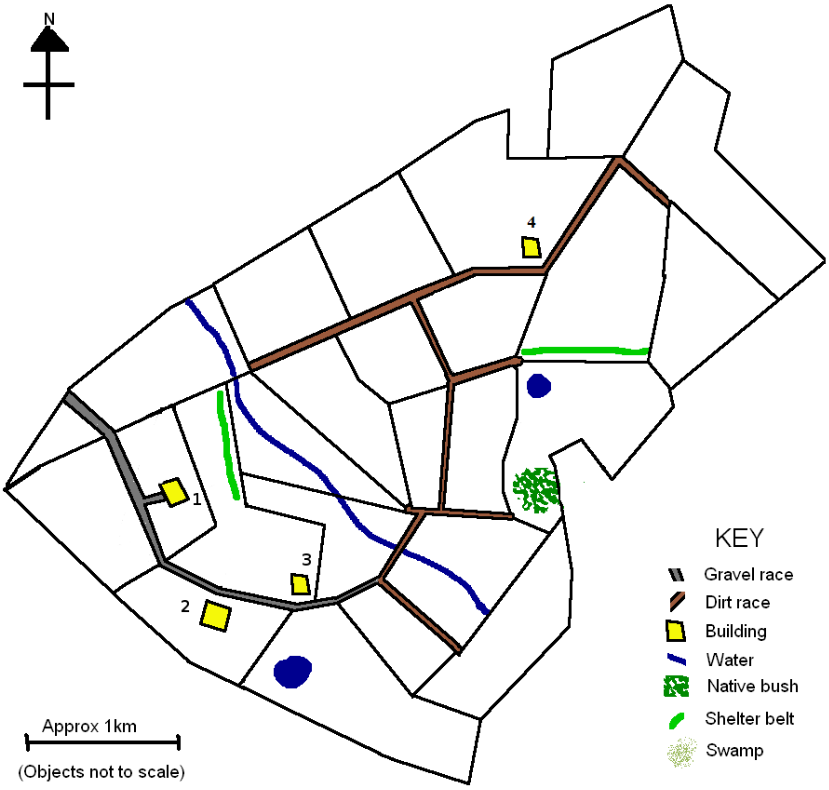


Figure D.1: Map of the sheep and beef farm

farm layout of paddocks, races, water and trees. The map shows where buildings are and whether they have mains power. Pictures of buildings and trees were supplied for reference.

- You are willing to put $4000 towards building the wireless network.

D.2 Dairy farmer

You are a 38 year old dairy farmer, married with two kids. You are a motorbike enthusiast and enjoy jogging. You are fairly comfortable using computers and would be keen to do Internet banking and online GST returns. You have heard good things about Fonterra's Fencepost.com portal for near real-time milk collection information and milk payout forecasts. It would also be great to be able to check long-term weather forecasts and communicate with your stock agent. Your 16 year old daughter works on the farm and would like to enroll in a web-based farming qualification next year. Both kids want to be able to Facebook their friends.

- Figure D.2 shows the map of the farm that was supplied showing the farm layout of paddocks, races, water and trees. The map shows where buildings are and whether they have mains power. Pictures of buildings and trees were supplied for reference.
- You are willing to put $6000 towards building the wireless network.

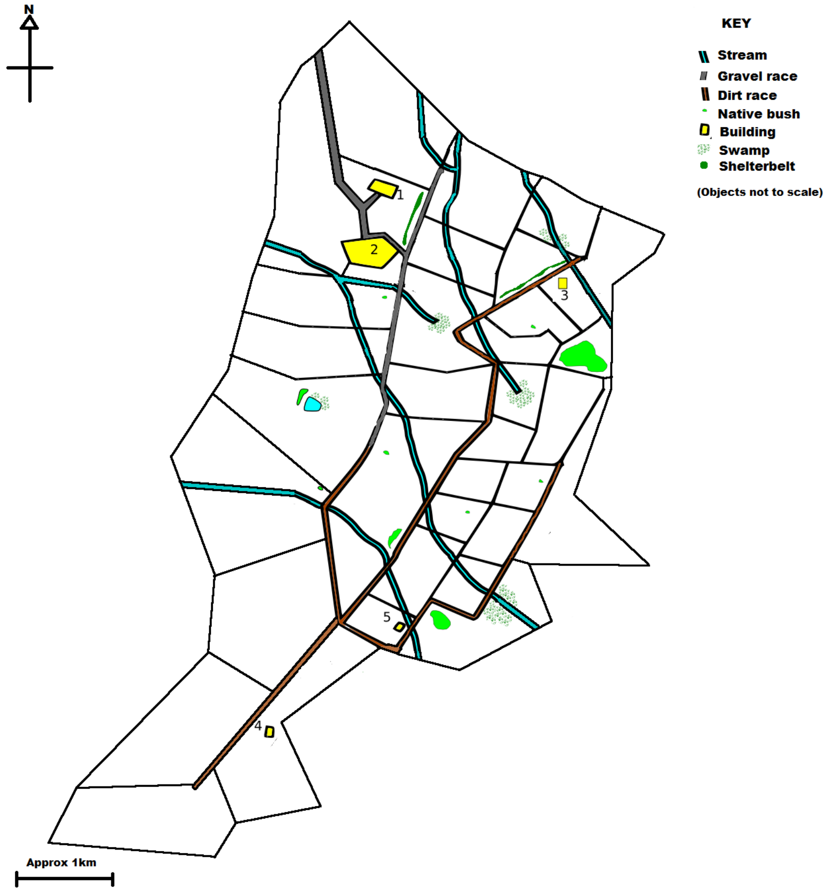


Figure D.2: Map of the dairy farm

D.3 School principal

You are the 35 year old principal of the local school. You are married with 9 year old twins and a 5 year old, all girls. You enjoy reading books and doing a bit of cooking. You are very comfortable using computers as you use them on a daily basis for administration work. You are convinced that rural kids are disadvantaged and that rural schools must have access to high-speed broadband now to help achieve the same educational objectives as urban children. Video conferencing with other schools would open up options and interactive online learning would become a possibility. Staff could be in contact with their peers and the Ministry of Education, providing support and teaching resources.

- The school principal was given an annotated aerial photo showing the main building
  - the building has an easting of 1928940m, northing of 5721931m and the roof is 6m high
- 3 teachers (including you)
- 58 pupils, mostly between the ages of 5 and 13
- 1 computer lab
- 2 offices (including yours)
- The school is willing to contribute $2000 towards building the wireless network

D.4 Community representative

You are 42 years old and enjoy hiking and cycling. You are fairly comfortable using computers and are a serious console gamer. You represent the Minginui community; most people want to be able to surf the web and send email while a few people want to be able to work from home and communicate with the office via Skype and video-conference. You are also aware of some people that do not wish to be involved and object to having wireless signals on their land. Gaming-wise, apart from a few games online at a friends place in Rotorua, you have been restricted to single player. You are itching to be able to jump online and deal out some serious fragging.

- The community representative was given an annotated aerial photo showing building locations
- The community representative was also given a list of the five highest trig stations in the area with the station location and access information
- There are approximately 75 buildings in Minginui
- Each household that wants to be part of the network has pledged between $50 and $100
- This means that there is a total of approximately $6000 towards the building of the wireless network

D.5 Cultural expert

You are a respected elder amongst your hapū and iwi. You are 62 years of age and through your lifetime you have learned much about the land and history of your people. You are married with four adult children and enjoy reading and gardening. You know a little about computers as you have been to a few workshops and feel relatively comfortable using them. Many of the older mokopuna have left the area to attend schools in other areas. It is your view that with a decent Internet connection opportunities could be offered at the local kura via video-conference and that as a result the mokopuna could stay in the valley with their whānau until the end of high school. Many members of the whānau are in other areas of New Zealand and the world, so the ability to Skype, email and Facebook would be used extensively. Though you believe that the network will bring much to your iwi, the network construction must respect the land. To this end, you are on hand to ensure that the sacred summits of local maunga are not built upon and that urupā sites and other areas of significance must be respected.

- Figure D.3 shows the map supplied to the cultural expert persona showing heritage sites in the Te Whaiti area.
- As you live in Minginui, you have already pledged some money towards building the wireless network.

Cultural respect Two Maori experts were consulted to ensure that the persona of the cultural expert was respectful and inoffensive. The persona of the cultural expert was provided with the Nga Taonga [21] of Ngati Whare, to acknowledge and show respect for the local iwi.

Nga Taonga I hare mai te mana a te iwi o Ngati Whare, mai nga wairua o ratau ma inga pai maunga a Tuwatawata me Moerangi. Te wairua a te awa o Whirinaki, ka pa i nga tipurana o Wharepakau. Te Whaiti Nui-a-Toi i hara mai tenei ingoa nga, nga matua tuku iho. Mai te timatana he te awa o Whirinaki. I taua wa ka tareka e koe ki te peke i te tahi taha ka hoki mai. Kai te ki matau i hara mai matau mai ia Toi. I te ra wa nga tangata whenua ko nga Marangaranga. Te wa o nga Marangaranga: he iwi manaki tangata, he iwi tipu kai, he iwi mohio nga ranoa, nga mahi nga kai, he iwi kaitiakitanga o nga whenua, ngahere, taonga tuki iho a kuia ma e koro ma. Hineruarangi ko ia te kaitiaki o Ngati Whare iwi. Ko Hineruarangi te tamahine a Toi, a noho ana aia i wahi tapu Te Whakamaru, ka puta mai ia pe nei te manu. Ka noho te mana nga tikanga, te kawa, me nga taonga korero tuku iho, a kuia ma e koro ma, mo ake tonu atu

English interpretation (the treasures) Know that we are Ngati Whare and our life-force is from the union of our sacred mountains Tuwatawata and Moerangi. The water of our Whirinaki River carries this to all descendants of Wharepakau where ever in the world they reside. Te Whaiti Nui-a-Toi, the narrow canyon at the top of our valley takes its name from our spiritual ancestor Toi, a great leader explorer and community builder who is famed throughout the Pacific. Toi visited our ancestors the people of this valley, Marangaranga and shared his knowledge with them. Theirs was a community where people cared for each other and visitors were generously included . They had learned and shared much about nature including its food and herbal medicines. They were guardians of the land and forests that sustained them and they treasured the knowledge that had been passed down to them by their wise elders. Toi's daughter Hineruarangi remains as the spiritual guardian of Ngati Whare and in this sacred place has protected our values and knowledge through times of hardship. Ngati Whare are the kaitiaki (guardians) of the Whirinaki Forest - a precious rainforest of international repute.

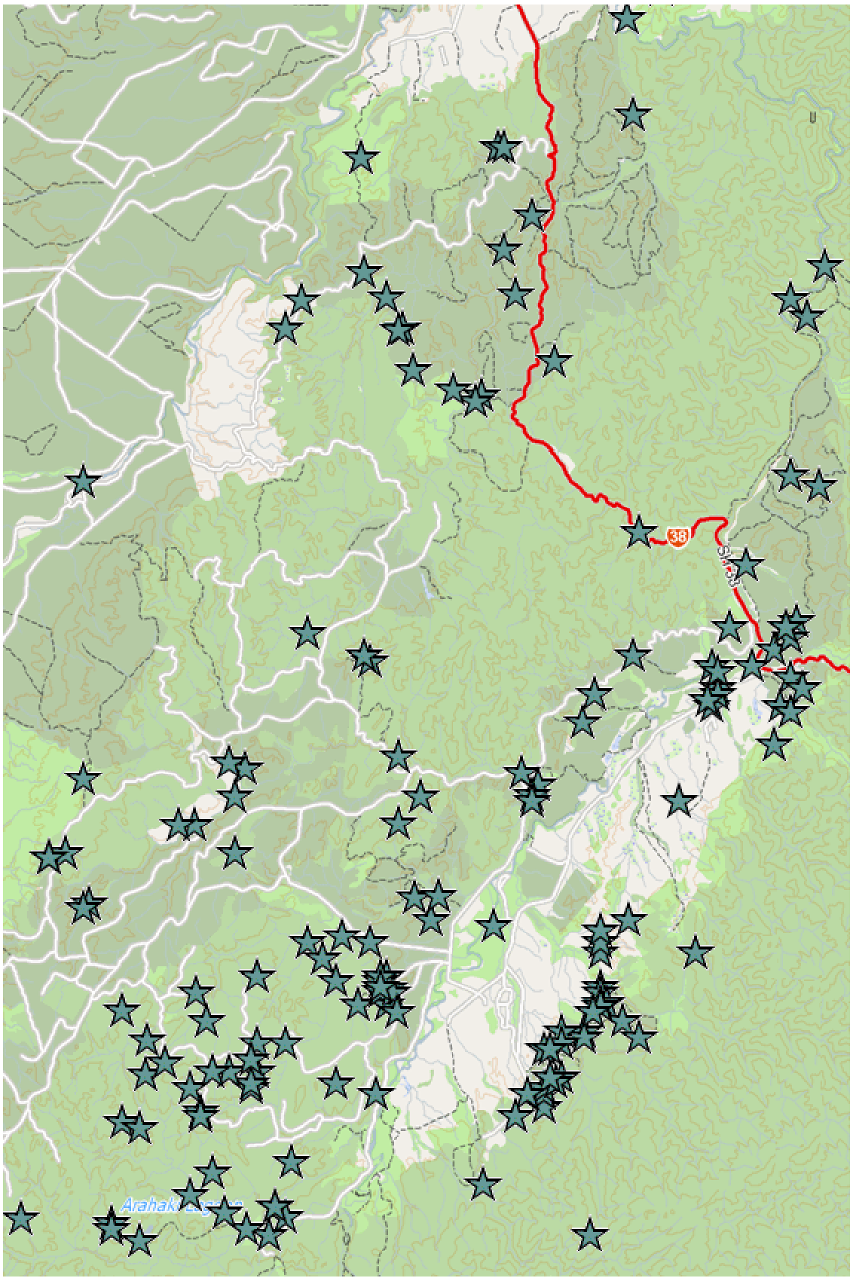


Figure D.3: Map showing heritage sites

Appendix E

Internet activities analysis

Whether people are from an urban community or a rural community does not greatly affect the activities that people find useful on the Internet. However, the reasons for finding those activities useful may be different for someone from a rural community compared to someone from an urban community. In 2009, Statistics New Zealand conducted a survey[1] of ICT in New Zealand [39]. Results from this survey are used to illustrate how popular various activities are among people from throughout New Zealand who have Internet access, including dial-up and broadband.

Survey results [39] showed that 90% of individuals surveyed used email and 46% used social networking. Results also showed that 26% of individuals used Internet telephony such as Skype. Video conferencing was used by 17% of individuals and 24% used other forms of communication such as chat rooms, message boards, instant messaging and blogging. Rural people want to be able to use these cheap reliable technologies to communicate with friends and family, like their urban counterparts. Farmers also want to be able to email their stock agent or check the current prices of wool, beef and milk.

Many rural people either operate a business from home, such as farmers,

[1]Results discussed were gathered from 2,677,000 individuals who accessed the Internet over twelve months

or choose to work from home some or all of the time. Rural people often live a significant distance from an urban centre where there are banks and shops, and for those people that work in these rural areas, it is difficult to find the time to run errands such as banking and GST returns. Instead it is much more convenient for rural people to conduct this business from home on the Internet, saving both time and money.

Rural people want better resources for their schools, as rural schools are often under-resourced compared to urban schools [86, 117]. Broadband Internet can introduce services such as video conferencing for running extra-mural courses and access to online teaching resources. In New Zealand, the Ministry of Education provides a web service to support teachers and provide resources. Internet at home would assist with children doing their home work. Some rural people may wish to further their education by completing online courses or training in their own time.

Rural people have a keen interest in the news and weather [81, 87]. Access to the Internet provides a wealth of news and weather services, including long-range weather forecasts.

Television and radio reception can be unreliable in rural areas so rural people may wish to source entertainment via the Internet. Survey results [39] showed that 39% of individuals surveyed used the Internet for downloading and listening to music and 34% downloaded and read books, newspapers and magazines. Movies, short films and images were downloaded and/or watched by 34% of individuals while 26% listened to web radio or watched web television. Computer games were played by 19% of surveyed individuals. It is not unreasonable to assume that rural people would have a similar interest in online entertainment, particularly given their physical distance from live entertainment venues, cinemas and movie rental stores.

Appendix F

WiPlan tutorial

Step 1

This tutorial will illustrate how to carry out key wireless network planning tasks. In order to begin the tutorial, try placing a house site at the spot marked X by right-clicking the X, selecting Create Site Here and clicking House.

Step 2

Now give your house site a name by right-clicking the house icon and selecting Site Properties. Enter the name "My house" or other name of your choosing. Check that the approximate antenna height is set to one storey. Notice the other options that we will return to later. Click OK.

Step 3

Note that relay and source sites can be placed and configured in the same way. Now try establishing a link between the house site and the existing source site denoted by the blue arrows. Right-click one of the two sites and select Create Link. Move the mouse to the other site and left click to bring up the Link Profile window.

Step 4

Now you should be able to see the Link Profile window. We are told that the link will not work because the link is obstructed by terrain. It can be seen that at least one antenna would need to be raised 50+ metres for the link to clear the hill. Click Cancel.

Step 5

This link is infeasible due to the terrain obstruction so right click the link and select Remove Link.

Step 6

It seems we need to place a relay to get to our new house site (you may need to zoom in). Explore the area by the spot marked X by right-clicking and selecting Explore Local Area.

Step 7

This looks like a pretty good spot for a relay - nice and high with a good view to the south and east. Close the Explore Local Area window and place a relay at the spot marked X (right-click and select Create Site Here -> Relay).

Step 8

Our new relay is too far away from mains power so lets change it to solar. Right-click the relay site and select Site Properties. Weather suitability shows a decent amount of sun so change the Power Source from mains to solar and observe the change in cost (cost increases as links are added).

Step 9

Notice that the relay has extra options compared to the source and house. Click Placement Examples and read the examples.

Step 10

For this tutorial assume we have permission and tick the box. Make up some notes. Now click Access Examples and read the examples.

Step 11

Select 4WD as dominant transport. Move the window to one side so you can see the relay and make notes about what you think access is like. When you are done click OK.

Step 12

Hover over the relay and notice the gray potential link showing that there is line-of-sight to the house. Create the link indicated by right-clicking a site, selecting Create Link and left clicking the site to link to. The dashed arrow gives a rough indication of whether there is line-of-sight between the site and the mouse pointer.

Step 13

The link has been calculated as line-of-sight and a cost given. The last step is for you, the user, to confirm that there are no possible obstructions such as trees and buildings that could block the link. Assume that the link is free of obstacles and click Yes.

Step 14

When a link is calculated as line-of-sight, the Link Profile window does not come up automatically. Right-click the link and select Link Profile. Un-tick the This Link Has No Obstructions check box and observe how the window changes. Now re-tick the box to change the link back to line-of-sight.

Step 15

Note there is a check box called This Link Is Active. Links can be activated and deactivated when experimenting with network designs. When deactivated, the link state changes to potential and the link's cost is no longer considered. Click OK.

Step 16

Look at the Site Properties for the relay, click Technical Information and observe the equipment listed. The cost of the relay is also updated (the same has happened for the house site). Click OK and OK again.

Step 17

You may have noticed that we only had one potential link when we were expecting two for our relay. Create a link between the relay and the source so we can figure out what is going on.

Step 18

We are told that the link is obstructed by terrain, the profile image shows there is a small knoll obstructing our relay. This is where local knowledge is useful as there is an un-powered barn that will give an extra 5m in height. Click Adjust Antenna Height for the relay and enter 9m as the height. Click OK.

Step 19

Knowing just how high an antenna can be put is often how non-line-of-sight (blocked by an obstruction) issues are solved. Make sure you tick the check box that This Link Has No Obstructions and click OK.

Step 20

Now we are going to compute a coverage plot. Right-click the source and select Compute Coverage. This will take approximately 10 seconds to finish.

Step 21

The coverage plot shows all points that should be reachable by this site within 2 km. Any neighbours in the coverage area could be connected to this site. We are going to revisit the house site and source site once again. Create a link between the two to bring up the Link Profile window.

Step 22

Now locate the highest hill obstructing our link. Click on the hill such that mouse cursor is at the correct x position (the y position does not matter). A message should pop-up telling you that a relay has been created.

Step 23

You could now use this relay to create an alternative path of links from the source to the house. It would then be possible to compare the costs, accessibility and placement issues of the two relays. Congratulations! You have completed the tutorial. Feel free to play around or load a real network plan to work on!

Appendix G

Radio wave propagation theory

G.1 Frequencies and line-of-sight

Radio wave propagation theory describes the propagation of radio waves in different environments. Radio waves travel at the speed of light (c) and can be expressed by the formula $f \times \lambda = c$ where f is the frequency in hertz and λ is the wavelength in metres. Wavelength describes the distance between consecutive corresponding peaks in the oscillating radio wave. Since speed is constant, as frequency increases, the wavelength decreases, and vice versa. Radio waves with longer wavelengths travel further, and are better at travelling through and around objects, however, radio waves with shorter wavelengths can transport more data [70].

A wireless channel is a specific frequency, allocated with a number or letter to identify it. Frequencies used for wireless communication belong to the radio spectrum, which is a subset of the electromagnetic radiation spectrum. These frequencies range from 300 Hz to 3000 GHz and the International Telecommunications Union (ITU) have categorized these frequencies into bands by their wavelength. Publicly available frequencies for wireless communication include 2.4 GHz, 5.4 GHz and 5.8 GHZ. Private frequencies used by protocols such as WiMax [89] fall within a similar range e.g. 3.5 GHz. These frequencies belong to the Ultra-High Frequency (UHF) and Super-High Frequency (SHF) bands designated by the ITU.

Frequency has an effect on radio waves propagation. Very low frequencies, in the order of kilohertz, have wavelengths in the order of kilometers and propagate along the surface of the earth due to electrical currents that flow in the ground [99]. Frequencies in the low megahertz range propagate by sky wave propagation where the radio waves transmitted from one location on earth can be refracted by the ionosphere back down to another location [99]. Shortwave radio is a well known example of sky wave propagation. For frequencies in the high megahertz range and above, the only way for the radio waves to propagate is directly between a transmitter and receiver, known as line-of-sight transmission. Line-of-sight means that the radio waves follow a direct path and that obstructions such as hills and trees can block the signal and cause undesired effects such as reflection and attenuation. Therefore, the path between the transmitter and receiver must be free of obstructions in order to achieve an efficient link.

Wireless line-of-sight is different than visual line-of-sight. As radio waves propagate, they also spread out the further they travel. Hence, an ellipsoidal volume of space known as the Fresnel zone needs to be considered. Equation G.1 shows how the radius of a Fresnel zone is calculated for a particular point P, where n is the Fresnel zone number, λ is the wavelength, $d_1$is the distance from the transmitter to P, and $d_2$is the distance from P to the receiver.

$$F_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}} \tag{G.1}$$

There are theoretically an infinite number of Fresnel zones as $n \to \infty$; however in wireless network planning, the innermost ($n = 1$) Fresnel zone is considered the most important. Figure G.1 shows an example of the innermost Fresnel zone. The size of the Fresnel zone is wavelength dependent because the wavelength determines the maximum radius/width of the ellipsoid. The significance

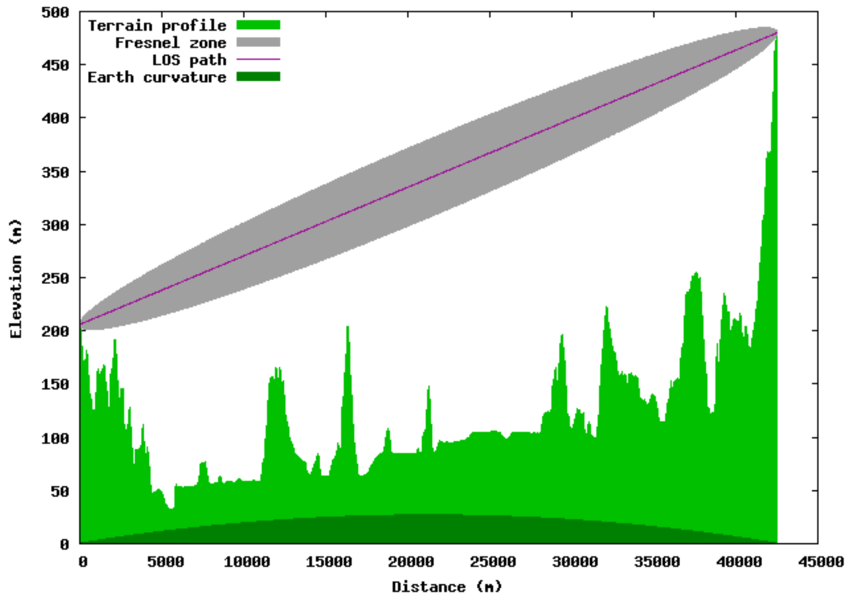


Figure G.1: Example of a path profile plot showing Fresnel zone

of the innermost Fresnel zone is that it defines the terrain clearance required to achieve wireless line-of-sight. Any obstacles, such as trees, buildings and mountains that obstruct the innermost Fresnel zone, will have an impact on radio wave propagation. Minor obstruction of the innermost Fresnel zone can be tolerated but is generally recommended by propagation experts to be less than 40% of the Fresnel radius at the point of obstruction [45].

G.2 IEEE 802.11 protocols

The selection of which protocol to use for a particular link directly determines the frequency that is used and maximum bit rate that can be obtained. The 802.11 protocols are discussed as they are the de-facto protocols for low-cost wireless devices throughout the world and operate on publicly available frequencies.

The IEEE 802.11 standards [36–38, 40], known as Wifi, define a set of protocols for use with publicly available frequencies. The original 802.11 protocol, now obsolete, was released in 1997 and provided only two bit rates, 1 Mbit/s and 2 Mbit/s. A bit rate is a measure of speed and refers to the number of bits that can be conveyed in a unit of time. In 1999, two amendments were made to 802.11(802.11a and 802.11b) which introduced higher bit rates.

The 802.11a protocol [37] operates in the 5 GHz band, in most cases between 5.150 and 5.320 GHz, and between 5.745 and 5.805 GHz. Due to the higher frequency, 802.11a is incompatible with, and less power efficient than, the other 802.11 protocols. 802.11a has eight data rates; 54, 48, 36, 24, 18, 12, 9 and 6 Mbit/s. The protocol supports up to 201 channels, however regulatory domains only use a small subset. For example, in the United States the Federal Communications Commission has selected 12 non-overlapping channels to make up the legal frequency range. WiPlan currently includes 802.11a as one of the protocol choices for link configuration.

The 802.11b protocol [36] operates between 2.400 and 2.495 GHz and has 14 overlapping channels. Different regulatory domains support different subsets of these channels but most include at least channels 1 to 11. 802.11b has four bit rates; 11, 5.5, 2 and 1 Mbit/s. The 802.11b protocol is highly susceptible to interference from other devices; including microwave ovens, cordless home phones and baby monitors.

The 802.11g amendment [38] to 802.11 was introduced in June 2003. 802.11g operates in the same frequency range as 802.11b; in this way 802.11g supports 12 bit rates in total, the same eight as 802.11a and four the same as 802.11b. This means that the two protocols are compatible; that is, 802.11g can revert back to the 802.11b bit rates if necessary. Since its introduction, 802.11g has become a standard feature on most laptops and handheld devices. As with 802.11b, significant interference can be experienced with 802.11g due to operating in the popular 2.4 GHz spectrum. WiPlan currently includes 802.11g as one of the protocol choices for link configuration.

The 802.11n protocol [40] is the latest amendment to 802.11, introduced in 2009. 802.11n operates in the 2.4 GHz range, however due to the use of Multiple-Input Multiple-Output (MIMO) [79] technology achieves bit rates of up to 600 Mbit/s. MIMO is a recent technology that uses multiple antennae in order to significantly increase throughput; however due to having multiple antenna, 802.11n devices are more costly than other 802.11 devices.

G.3 Antenna selection

Antenna selection is an important decision in wireless network planning. Different antenna types of antennas are used for different scenarios. Wireless network planning tools should be capable of automatically selecting antenna to be used for a particular scenario, for example, creating a point-to-point link. This section describes key aspects of antenna behaviour that a wireless network planning tool such as WiPlan needs to consider.

The isotropic antenna is a fundamental concept in wireless network planning. The isotropic antenna is a theoretical 100% efficient antenna that radiates energy equally in all directions as a perfect sphere. This theoretical isotropic antenna forms a basis for comparing antennas. The gain of an antenna is the ratio between the power required at the input of an isotropic antenna and the power required at the input of the real antenna being considered, such that the power intensity in a given direction is the same for both antennas. Gain is measured in decibels relative to the isotropic antenna (dBi). The direction of maximum gain is often used for the categorization of antennas.

Radiation patterns show the way an antenna propagates radio waves in both the horizontal and vertical directions. Radiation patterns can be summarised by the azimuth and elevation/zenith. The azimuth describes the angle of direction in the horizontal plane; the elevation describes the angle above and below the horizontal i.e. in the vertical plane. As an example, the direction of maximum gain for an omni-directional antenna is in the horizontal direction with an azimuth of 360 degrees but an elevation of only a few degrees. These sort of antenna are used as access points to provide network coverage to public or common areas in mostly-flat areas. Highly directional antenna have very precise azimuths and elevations of only a few degrees.

Directional antenna come in a range of form factors that influence the size and shape of the directional beam they form for both transmission and reception. Directional antenna have a number of benefits over omni-directional antenna. Since the beam is more focused, the potential range of the antenna is increased and the possibility of interference is reduced. Directional antenna conserve bandwidth and energy consumption, making them an excellent choice for long-distance links [61]. The gain of directional antenna typically range from 15 dBi to 30 dBi for point-to-point links over distances up to 40 km [55].

Electro-magnetic radiation waves consist of electric and magnetic fields travelling in the same direction but perpendicular to each other. Polarity describes the direction of the electrical field vector. A vertically aligned antenna will transmit radio waves that have vertical electric fields and horizontal magnetic fields, a horizontally aligned antenna will be the opposite. Interference can occur when the receivers of two separate links are in close proximity to each other with the same frequency and antenna polarisation. This interference can be mitigated by using vertically polarised antennas for one link and horizontally polarised antennas for the other link. Links using vertically polarised antennas experience higher signal attenuation than links using horizontally polarised antennas in wooded areas due to radio wave scattering upon impact with the vertical tree trunks [34]. Horizontal polarisation is the better choice for urban areas with tall buildings while vertical polarisation is better when the link is across water to prevent reflection off the water . Signal polarisation can also be altered by heavy rainfall due to the non-spherical shape of large raindrops [33].

G.4 Signal and noise

Tools for wireless network planning need to have signal strength and noise support in order to determine the performance of an arbitrary link. This section describes why signal strength and noise are fundamental for wireless network planning.

The radio wave that is being propagated is referred to as the signal and at any moment in time that signal has a particular strength. This signal strength is measured in decibels and is relative to one milliwatt, hence signal strength is expressed in decibel milliwatts (dBm). A signal strength of 0 dBm is equivalent to 1 milliwatt of power. Positive values mean that the signal is stronger than 1 milliwatt and negative values indicate that the signal is weaker than 1 milliwatt. Every +3 dBm is a doubling in power and every -3 dBm is a halving in power (3 dBm = 2 milliwatts, -3 dBm = 0.5 milliwatts).

Effective isotropically radiated power (EIRP) is an important measure of signal. This is the peak amount of power that would be emitted by a theoretical isotropic antenna in the direction of the antenna's maximum gain. EIRP also takes in to account losses sustained in the connectors and cables. Equation G.2 shows the formula for calculating EIRP, where P_{tx} is the power of the transmitter in dBm, L_{tx} is the loss in dB due to connectors and cables, and G_t is the antenna gain in dBi.

$$EIRP = P_{tx} - L_{tx} + G_t \; dB \tag{G.2}$$

Regulations are often put in place to restrict the maximum EIRP in a given area. This is usually to minimise interference on similar frequencies. Most governments around the world have a working group that determine these regulations across the radio spectrum for their region.

Signal strength can be measured at any point in the path between the transmitter and the receiver; the first of which is when the signal is transmitted from the radio itself. At this point, the power measured is that generated by the radio and is known as transmit power. The signal strength is then increased relative to the gain of the transmitting antenna as the signal radiates out from the transmitting antenna. The receiving antenna increases the signal strength relative to the gain of the receiving antenna as the signal is received by the receiving antenna and finally the signal reaches the radio receiver.

Each bit rate is transmitted at a particular transmit power and has to be received above a certain signal strength, the receive sensitivity, in order for the signal to be correctly decoded. The 802.11 standard [35] defines receive sensitivity as the minimum signal level required for packet loss to exceed 3%. As bit rate increases, the transmit power and/or the receive sensitivity must also increase in order to meet the 3% packet loss requirement. Transmit power is limited by EIRP restrictions therefore receive sensitivity is different for each bit rate. The receive sensitivity is between -95 dBm and -70 dBm for 802.11 protocols.

Noise is any unwanted radio transmissions that occur on or near the operating frequency. Most frequency bands used by 802.11 wireless equipment are in the unlicensed public spectrum. This means that network planners must not only consider transmissions from other wireless networks but also transmissions from cordless phones, Bluetooth and some electrical devices such as microwave ovens. Noise is a problem when it exceeds the power of the desired signal. Enge et. al. show average noise measurements of -85.1 dBm and -97.1 dBm at two different rural study sites [66].

A common measure used by wireless network planners to gauge the performance of a link is the signal to noise ratio (SNR). This is the ratio between the desired signal and unwanted noise. Since both signal and noise are measured in the logarithmic decibel scale, the signal-to-noise ratio can be calculated by simply subtracting the noise from the signal.

G.5 Loss

In wireless network planning, loss refers to the loss of power between a transmitter and receiver in decibels (dB). Understanding the factors that influence that loss, known as propagation loss, is necessary for predicting whether the performance of an arbitrary link will be satisfactory. This section describes the how propagation loss occurs and the effects that might result.

When a wireless signal is transmitted, radio waves radiate out from the antenna. Phenomena such as reflection, absorption, refraction, diffraction and scattering can occur as a result of obstructions that lie in the path of the radio waves. The most common phenomena are reflection and absorption. Radio waves reflect off most surfaces, also losing some of their power due to absorption. This includes dense grids of bars or mesh, as long as the distance between the bars/mesh is small compared to the wavelength of the radio wave. For example, a one centimeter metal grid will appear as a solid metal plate at a frequency of 2.4 GHz with a wavelength of 0.125m (12.5 cm). Some obstructions allow radio waves to pass through them, absorbing some of the power in the process, depending on the frequency.

Refraction of radio waves can be caused by the atmosphere [31] and by man-made products with a different refractive index than air, such as glass or water. The planner needs to consider the possibility of propagation loss due to the effects of water bodies when planning any links over water. Very large expanses of water can have an interesting effect called ducting. This is when there is a refractive index difference between the atmosphere and the water which creates a duct that behaves like a giant optical fiber. The radio wave becomes trapped in the duct and can travel great distances with low loss [78]. Diffraction [41] occurs when radio waves encounter the edge of an obstacle, such as the top of a building or a mountain. Diffraction causes the radio waves to bend around the obstacle which can be used to the network planners' advantage, however loss in signal strength will also result. Scattering is a form of reflection and occurs when the obstruction is non-uniform, such as the branches and leaves of trees.

With all of these phenomena, a signal can arrive at its destination via many distinct paths, and sometimes not at all. This occurrence is commonly known as multipath. Changes in amplitude and phase may occur as a result of the different reflections of the signal travelling via different paths. These differences in path distance result in different time of arrivals. Radio waves are considered to be sinusoidal waveforms and when reflections of the signal arrive at a receiver, they combine to form a single waveform for the receiver to decode. Constructive interference occurs when two peaks coincide, resulting in increased power. When a peak and a valley coincide, destructive interference occurs and the receiver will be unable to decode the signal. Multipath is difficult to predict, therefore it is important that the effects of multipath are minimized as much as possible during the wireless network planning process.

Loss can change dramatically over time. The timing variation experienced by loss is known as fading. Fast fading is when the loss changes rapidly, such as during the transmission of a single frame on a mobile network. Slow fading occurs in the order of seconds and is due to changes in terrain and atmospheric conditions. Flat fading is when the variation of loss is small and almost uniform in comparison to the radio system bandwidth. Frequency-selective fading is when there are large signal variations over the system bandwidth and certain frequencies may be severely affected while others are not affected at all.

Fading is often statistically modelled in one of two ways. Rayleigh fading represents scenarios where there are multiple indirect paths between the transmitter and the receiver, with no distinct dominant path, such as in an urban canyon where there are many high buildings that can cause reflection or diffraction of the signal. The signals arriving at the receiver are modelled as the sum of multiple, independent, random variables. Where a dominant, usually direct, path exists, then Ricean fading is more appropriate as Ricean fading generates a stochastic distribution around a more consistent mean.

G.6 Classification of transmission loss

The ability to classify transmission loss is important as classification specifies where the loss was measured. Consistent use of terms and definitions ensure that the link budget is understood and provides a useful way to describe how the propagation models work. The ITU recommends that the following terms and definitions are used when describing transmission loss for radio links [28]. Figure G.2 provides an illustration of these terms and definitions. All of the following loss types are expressed in decibels.

Total loss Total loss (L_l) is the ratio between the power supplied by the radio transmitter and the power supplied to the radio receiver. The exact point in the radios at which the power is measured should be specified. In this research, some addition terms need to be defined. P_{tx} is the power at the terminals of the radio transmitter and P_{rx} is the power at the terminals of the radio receiver. Losses incurred by feed lines (cables) and connectors are denoted by L_{tx} and L_{rx} for the transmitter and receiver respectively.

System loss System loss (L_s) is ratio between the power at the terminals of the transmitting antenna (P_t) and the power at the terminals of the receiving antenna (P_a). System loss can be expressed by $L_s = P_t - P_a$ dB.

Transmission loss Transmission loss (L) is the ratio between the power radiated by the transmitting antenna and the power at the receiving antenna output if there were no losses in the antenna circuitry. Transmission loss can be expressed by $L = L_s - L_{tc} - L_{rc}$ dB where L_{tc} are the transmitting antenna losses and L_{rc} are the receiving antenna losses.

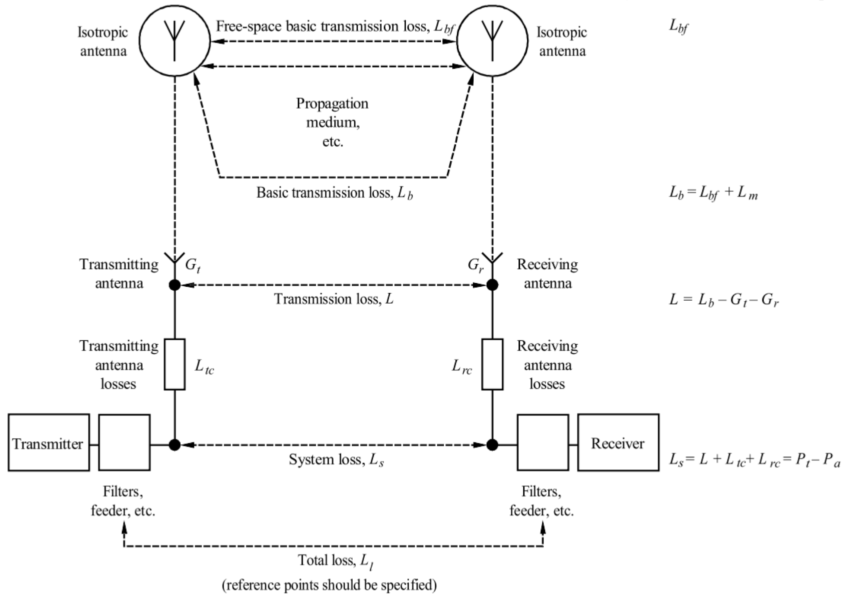
Basic transmission loss Basic transmission loss (L_b) is the transmission loss that would occur if the antennas were replaced with isotropic antennas but including the effects of radio wave propagation phenomena. Basic transmission loss can be expressed by $L_b = L + G_t + G_r$ dB where G_t and G_r are the gains of the transmitting and receiving antennas respectively.

Free-space basic transmission loss Free-space basic transmission loss (L_{bf}) is the transmission loss that would occur if the antennas were replaced with isotropic antennas and those antennas were located in free-space.

Ray path transmission loss Ray path transmission loss (L_t) is the transmission loss for a particular ray propagation path and can be expressed by $L_t = L_b - G_t - G_r$ dB.

Loss relative to free-space Loss relative to free-space (L_m) is the difference between the basic transmission loss and the free-space basic transmission loss. Loss relative to free-space may be the summation of several independent calculations. For example, incorporating loss calculations from multiple vegetation sources. Loss relative to free-space can be expressed by $L_m = L_b - L_{bf}$ dB.

Figure G.2: Classifications of transmission loss (sourced from [28])



G.7 Link budget

A link budget can be used to determine if a link configuration is acceptable by accounting for all of the gains and losses in a wireless link [111]. These gains and losses can be expressed with Equation G.3.

$$P_{rx} = P_{tx} - L_{tx} + G_t - L_{tc} - L_{bf} - L_m + G_r - L_{rc} - L_{rx} \tag{G.3}$$

TX and RX refer to the transmitting and receiving stations respectively. The transmitting station has a radio with an output power (P_t) in dBm and an antenna with gain (G_t) in dBi and associated antenna losses (L_{tc}) in dB. The receiving station has a radio with a receive sensitivity that the received power (P_{rx}) must meet or exceed; P_{rx} therefore represents that receive sensitivity. The receiving station also has an antenna with gain (G_r) in dBi with associated antenna losses (L_{rc}) in dB. Both stations have extra losses that can be attributed to cables and connectors, which are represented by L_{tx} and L_{rx}. Free-space loss is represented by L_{bf}. Loss relative to free-space (L_m) can be derived using propagation modeling, fading modeling or by providing a margin value; a margin value of 10 dB will satisfy most situations .

The *basic transmission loss* can be calculated by re-arranging Equation G.3 to obtain Equation G.4. It is then possible to determine, using propagation modelling, whether a particular link configuration will satisfy the link budget. Determining the basic transmission loss (L_b) in this way indicates the maximum loss that is acceptable for the link configuration (note that L_{bf} and L_m have been replaced with their sum L_b).

$$L_b = P_{tx} + G_t - L_{tx} - L_{tc} + G_r - L_{rx} - L_{rc} - P_{rx} \tag{G.4}$$

G.7.1 Example

The transmitting radio has an output power of 18 dBm and is connected to a 26 dBi antenna. The receiving radio has a receive sensitivity of -90 dBm and is connected to a 26 dBi antenna. Cable and connector losses at each end are assumed to be 1 dB and the antenna losses are assumed to be 0 dB. These values are then used in Equation G.4 as follows:

$$L_b = 18dBm + 26dBi - 1dB - 0dB + 26dBi - 1dB - 0dB - -90dBm$$

hence $L_b = 18 + 26 + 26 + 90 - 1 - 0 - 1 - 0 = 160 - 2 = 158\,dB$

This indicates that the performance of the link will be satisfactory with a propagation loss of up to 158 dB. Antenna gains will need to be increased and/or the bit rate lowered to reduce the receive sensitivity if the propagation loss exceeds 158 dB. It is common to add a safety margin to this loss in addition to L_m. For example, a safety margin of 10 dB may be introduced, such that the propagation loss is considered satisfactory up to 148 dB.

Appendix H

Example area profile configuration

```
# Example config file for areaprofile (C) Sam Bartels 2009
InputFilename = "/home/sam/gis/dem/w001001.adf"
OutputFilename = "/home/sam/test.png"
# Specify bounding box of interest
GeoBoundingBox{

    # Type of coordinates for bounding box (NZTM, WGS84)
    CoordType = "NZTM"
    # Northern-most coordinate
    NorthLimit = 5721327.37
    # Southern-most coordinate
    SouthLimit = 5717327.37
    # Eastern-most coordinate
    EastLimit = 1929563.04
    # Western-most coordinate
    WestLimit = 1925563.04
}
```

```
Site {

    # Name of site
    Name = "Tom's house"
    # Location of Transmitter
    Location {
        # Coordinate type (NZTM, WGS84)
        CoordType = "NZTM"
        # Easting or Longitude coordinate
        X = 1927563.04
        # Northing or Latitude coordinate
        Y = 5719327.37
    }
    # Antenna settings
    Antenna {

        # Height of antenna above the ground in metres
        Height = 4.0
        # Orientation of antenna in degrees
        Orientation = 0.0
        # Azimuth of antenna in degrees
        Azimuth = 360.0
        # Tilt of antenna in degrees (-ve indicates down)
        Tilt = 0.0
        # Elevation of antenna in degrees
        Elevation = 30.0
        # Maximum transmit distance to consider in metres
        TxDistance = 2000.0
    }
```

```
# System variables
System {
    # Maximum path loss allowed
    PathLossLimit = 148.0
    # Frequency of system in Mhz
    Frequency = 5400.0
    # Polarity of system (0=horizontal, 1=vertical)
    Polarity = 0
}
# Environmental constants
Environment {
    # Dielectric Constant of Ground
    GroundDielectric = 15.0
    # Conductivity of ground (S/m)
    GroundConductivity = 0.001
    # Surface refractivity (N-units)
    SurfaceRefractivity = 301.0
    # Radio climate: 1-Equatorial, 2-Continental Subtropical,
    # 3-Maritime Tropical, 4-Desert,
    # 5-Continental Temperate, 6-Maritime Temperate,
    # Over Land, 7-Maritime Temperate, Over Sea
    RadioClimate = 6
}
```

```
    # Other variables
    Other {
        # Height of RX antenna in metres
        RxAntennaHeight = 4.0
        # Measure of time variability
        TimeVar = 0.5
        # Measure of location variability
        LocVar = 0.5
        # Measure of situation variability
        SitVar = 0.5
    }
}
```

Appendix I

Ethics approval

Computing and Mathematical Sciences
Rorohiko me ngā Pūtaiao Pāngarau
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Hamilton
New Zealand

Phone +64 7 838 4021
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THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

29 November 2010

Sam Bartels
C/- Department of Computer Science
THE UNIVERSITY OF WAIKATO

Dear Sam

Request for approval to conduct an evaluation for your PhD research project "An interface for Wireless Network Planning".

I have considered your request to conduct a research study with human participants for the purpose of evaluating a system (WiPlan) for helping people to create a wireless network plan for their local rural area.

The procedure described in your request is acceptable, particularly noting your consultation with experts on Maori customs.

I note that the information gathered will form a chapter of your PhD thesis and a possible research paper. No identifying information about the participants will be published and any information provided by them and used in publications, will be anonymised. All collected data, recordings and documents will be kept securely in the FCMS Data Archive until 28 February 2013 and then destroyed.

The research participants' information sheet and consent forms meet the requirements of the University's human research ethics policies and procedures.

Yours sincerely,

Masood Masoodian
Human Research Ethics Committee
School of Computing and Mathematical Sciences

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