UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

AN OPTIMAL COMMERCIALLY AVAILABLE WIRELESS SENSOR NETWORK IN VITICULTURE

by

Jan-Georg van der Wath

Submitted in partial fulfilment of the requirements for the degree
Master of Engineering (Computer Engineering)

in the

Department of Electrical, Electronic and Computer Engineering
Faculty of Engineering, Built Environment and Information Technology

UNIVERSITY OF PRETORIA

15 August 2015

SUMMARY

AN OPTIMAL COMMERCIALLY AVAILABLE WIRELESS SENSOR NETWORK IN VITICULTURE

by

Jan-Georg van der Wath

Supervisor:	Prof G.P. Hancke
Department:	Electrical, Electronic and Computer Engineering
University:	University of Pretoria
Degree:	Master of Engineering (Computer Engineering)
Keywords:	Wireless sensor network (WSN), precision agriculture, viticulture, DASH7, ZigBee, quad-copter, technology assessment (TA), Fresnel zone, South Africa, commercial

For more than a decade research in wireless sensor networks has received much attention. Several wireless sensor network standards have been proposed and are still being developed. In precision agriculture, specifically viticulture, wireless sensor networks have been proven as advantageous, but widespread implementation of such systems is still lacking in the South African wine farm industry. Investigating what the specific requirements of a wireless sensor network for a South African viticulturist are, and assessing the existing commercial systems available, can provide better insight into the reason for their slow implementation. The researcher has identified a feasible commercially available system and by using the identified requirements, proposes a system as an optimal solution for wireless sensor networks to be implemented at a South African wine farm.

The cost of the sensor systems is the most important factor for a wine farmer. This challenges the design paradigm of wireless sensor networks, where nodes are deployed in redundant fashion to create a network of nodes capable of routing packets over several different routes to the same destination. The focus shifts to deploying nodes more sparsely, capable of greater

communication distance. Thievery is of concern as well and poses the problem of increasing the risk of theft by installing sensors within line of sight together with solar panels. Placing the nodes on the ground, out of sight, causes interference with the radio signal and reduces the communication distance drastically. Since solar panels are not feasible due to theft, batteries will have to last at least one season.

The DASH7 wireless standard meets the longer communication distance and extended battery life requirements, and coupled with autonomous quadcopters is a promising optimal solution. Nodes will not have to be in line of sight since the drone flies directly overhead and initialises communication to retrieve the sensor data. The BLAST principle that the DASH7 standard uses fits in with this approach and should be investigated more thoroughly, but commercial implementation of it has to wait until the development of the standard is completed.

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

OPSOMMING

‘N OPTIMALE KOMMERSIËLE BESKIKBARE DRAADLOSE SENSOR NETWERK IN WINGERDE

deur

Jan-Georg van der Wath

Studieleier:	Prof G.P. Hancke
Departement:	Elektriese, Elektroniese en Rekenaar-Ingenieurswese
Universiteit:	Universiteit van Pretoria
Graad:	Magister in Ingenieurswese (Rekenaar Ingenieurswese)
Sleutelwoorde:	Draadlose sensor-netwerk, presisie-landbou, wingerdbou, DASH7, ZigBee, robotvliegtuig, tegnologie-beoordeling, Fresnel sone, Suid-Afrika, kommersieel

Vir meer as ’n dekade het navorsing in draadlose sensor-netwerke heelwat aandag ontvang. Verskeie draadlose sensor-netwerk standaarde is voorgestel en is steeds onder ontwikkeling. In presisie-landbou, spesifiek wingerdbou, is draadlose sensor-netwerke reeds as voordelig bewys. Die wydverspreide implementering van sisteme van so aard in die Suid-Afrikaanse wynbedryf lei egter steeds gebrek. Die spesifieke behoefte aan ’n draadlose sensor-netwerk vir ’n Suid-Afrikaanse wingerdboer, asook die waardebepaling van kommersiële sisteme wat tans beskikbaar is, is ondersoek, om sodoende beter insigte te verskaf rakend die redes vir die stadige implementering daarvan. ’n Uitvoerbare kommersieel-beskikbare sisteem is geïdentifiseer en deur gebruik te maak van die geïdentifiseerde vereistes is ’n sisteem voorgestel wat as optimale oplossing vir draadlose sensor-netwerke vir ’n Suid-Afrikaanse wynplaas kan dien.

Die koste van sensor-sisteme is die belangrikste faktor vir ’n wynboer. Dit veroorsaak teenstrydigheid met die ontwerp-paradigma van draadlose sensor-netwerke waar nodusse in ‘n oorbodige wyse geïnstalleer word. Gevolglik word ’n netwerk geskep waar nodusse in staat is om pakkies via verskeie roetes na ’n eindbestemming te kan stuur. Die fokus verskuif

daarna om nodusse eerder yl te installeer met groter kommunikasie-afstande tussen in. Diefstal is ook ’n bekommernis en die installasie van sigbare sensors en sonpanele word dus ’n hoër risiko. Die installasie van die nodusse op die grond en buite sig, veroorsaak steurings in die radio sein en gevolglik word die kommunikasie reikafstand drasties verminder. Omdat die installasie van sonpanele buite die kwessie is, moet ’n battery se leeftyd ten minste een seisoen duur.

Die DASH7 draadlose standaard voldoen aan die vereistes vir ‘n langer kommunikasie-afstand en verlengde battery-leeftyd. Die verbinding daarvan met die outonoom vier-propeller helikopters beloof om ’n optimale oplossing daar te stel. Nodusse kan dus buite sig geïnstalleer word, met die robotvliegtuig wat direk bo-oor vlieg en kommunikasie bewerkstellig om sodoende die sensor-data te onttrek. Die BLAST beginsel wat deur DASH7 gebruik word, pas in by dié benadering en behoort in meer diepte ondersoek te word. Tog kommersiële implementering daarvan sal moet wag totdat die ontwikkeling van die standaard voltooi is.

ACKNOWLEDGEMENT

I would hereby like to acknowledge and thank each and every person who helped me with this research:

- Firstly, my supervisor, professor Gerhard Hancke, who provided me the opportunity to do this research and for his guidance and support.
- Mr. Guillaume Nel, for allowing me access to Aaldering wine estate and to conduct measurements there. Also for the active role he played in sharing his requirements for a sensor system that he wants to implement at Cavalli Estate and the solutions he implemented at Aaldering wine estate.
- Mr. Bob Hobson, viticulturist at Morgenster, for granting me the interview about sensor systems he has implemented and would find useful.
- Drikus Heyns and Isabel Habets, viticulturists at Distell for their insights into the role of wireless sensor networks in their vineyards and the practicality thereof.
- Pieter La Grange for lending me his quadcopter and services as pilot.
- My work colleagues, Andries Maritz and Mel van Rooyen, for their help in setting up the FEKO simulations and explaining the antenna domain to me.
- Mr. Izak Theron for helping me with measuring antenna characteristics.
- Izak Marais for his encouragement and guidance.

I would also like to thank the following organisations for their role:

- The Centre for Telecommunication Engineering for the Information Society (CeTEIS), its industry partners and THRIP for their generous study grant.
- EMSS SA, my employer, for granting me study leave.

Lastly, I thank my family and friends. This research would not have been possible without their kind support. I especially thank my wife for her emotional support and encouragement as well as being deprived of social time to allow me to study. I thank God for His blessings in opportunities and all the people involved who helped me.

LIST OF ABBREVIATIONS

ACK	acknowledgement packet
APO	application programmable object
APS	application support
ARQ	automatic repeat request
BLAST	bursty, light-data, asynchronous and transitive
CAP	contention access period
CBA	cost benefit analysis
CFP	contention free period
CH	cluster head
CLSMP	continuous logging soil moisture probe
CSMA	carrier sense multiple access
CSMA-CA	carrier sense multiple access collision avoidance
DSSS	direct sequence spread spectrum
FEC	forward error corrections
FFDs	full function devices
GTS	guaranteed time slots
HARQ	hybrid automatic repeat request
IR	infrared
ISO	International organization for standardization
MAC	medium access control
NDVI	Normalized Difference Vegetation Index
O-QPSK	offset quadrature phase shift keying
PAN	personal area network

QoS	quality of service
RF	radio frequency
RFID	radio-frequency identification
RFDs	reduce function devices
RSSI	received signal strength indication
TA	technology assessment
TDMA	time division multiple access
TSMP	Time synchronise mesh protocol
UV	ultra violet
VSWR	voltage standing wave ratio
WMED	Weissberger’s modified exponential decay
WSN	wireless sensor network
WSNs	wireless sensor networks
XLP	cross-layer protocol

TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION

1.1 PROBLEM STATEMENT

1.1.1 Context of the problem

Since the beginning of the millennium, research in wireless sensor networks (WSNs) has received a great deal of attention, but introduction into the commercial markets seems to be slow (Wang, Zhang & Wang, 2006). A wireless sensor network is a group of individual sensor nodes capable of communicating with each other via a wireless communication channel. These sensors gather (sense) information about their immediate environment, relaying that information through the other sensors in the network to a central node, called the sink. The type of data gathered differs according to the specific application for the network. The theory behind possible applications for WSNs states an immense amount of positive gain and advantages (Xia, 2009). One such field of application is in agriculture where the sensor network can be deployed to monitor the current conditions of the crop, and enable the farmer to react quickly on the conditions, ensuring the perfect condition for his crop to yield a higher harvest (Ruiz-Garcia, Lunadei, Barreiro & Robla, 2009; Panchard 2008; Piromalis, Arvanitis & Sigrimis, 2013; Deljoo & Keshtgari, 2012; Yu, Wu, Han & Zhang, 2012; Singh & Bansal, 2011; Lei Xiao & Lejiang Guo, 2010).

Vineyards are especially sensitive to the surrounding conditions and the grape farmers already monitor their grapes daily for decisions. Currently, such wireless sensor network (WSN) systems have only been commercially implemented in developed countries such as the United States of America and Europe and researched in developing countries such as India (Panchard, 2008). The winelands of South Africa have a rich history and produce some of the world's best wines, but water is a scarce commodity and according to predictions could become scarcer. Implementing WSNs throughout the South African winelands could possibly help improve the production quality of the grapes, lower inset costs and save water by better control of irrigation.

1.1.2 Research gap

The promise, such as providing a means to save water in water scarce areas, which WSNs can, is immense. The general conclusion is that such WSNs are highly feasible, scalable and useful (Wang, Wang, Qi, Xu, Chen & Wang, 2010). Unfortunately, current real world implementations of WSNs seem to be scarce and lagging behind their promises (Abbasi, Islam & Shaikh, 2014; Wang *et al.*, 2006). It is however a field which requires in-depth knowledge of both the application domain and sensor configurations, which makes widespread implementations difficult (Lewis, 2004). Working towards the objective of helping the farmers and monitoring the irrigation and water levels, several sources of literature exist (Singh & Bansal, 2011; Obalum, Ezenne, Watanabe & Wakatsuki, 2011), together with a satellite monitoring system implemented in the Cape winelands (Rinaldo & Klaasse, 2011). Various studies are still being done on the different applications for WSNs, most of which feature scarce resource objectives (Rashvand, Yi & Cui, 2011). The EMMON system architecture project is busy with research in implementing a feasible commercially available sensor network (Tennina, Bouroche, Braga, Gomes, Alves, Mirza, Ciriello, Carrozza, Santos & Garg, 2011)

Figure 1.1 illustrates where this research fits into the broader field of WSN research. This work generally aims to model the requirements that a WSN must adhere to for viticulture purposes to be easily implemented. The researcher of this dissertation has assessed current commercially available WSNs, and this model of requirements has been used to find the most suitable system and how to optimise the system further.

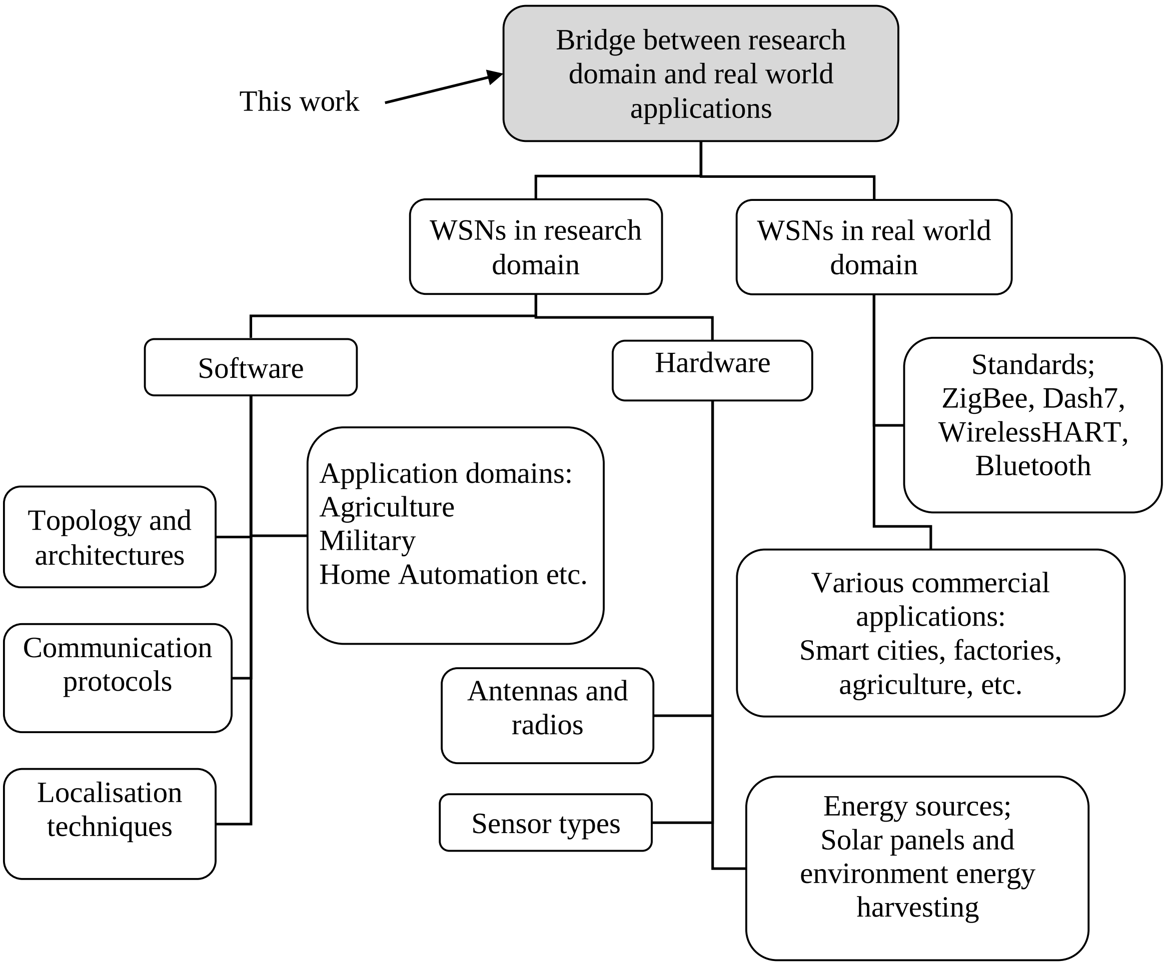

Figure 1.1. Focus of this research problem relative to its broad field of study

1.2 RESEARCH OBJECTIVE AND QUESTIONS

Through this research, starting with viticulture, the objectives and goals were to assess the current available WSN technologies and find the best implementation in architectures and protocols. The knowledge gained had to be sufficient to help with the widespread commercial implementation of such networks and to expand the implementation to different areas such as mining and construction. The following are the research questions:

- What results, with regards to the most optimal protocols and architecture, have been concluded with current and previous research done on WSNs in viticulture implementations?

- Is it possible to apply the most optimal implementation on a WSN which is commercially available?
- Is it possible to improve on the protocols and architecture, and what development and/or modifications are required to implement such a system from commercially available WSNs?
- What are the risks involved in implementing a WSN in the vineyards of South Africa?
- What are the advantages that can be gained with access to the additional environmental information, specifically for the viticulturist and farmer?
- What types of information are useful to the viticulturist and farmer and which of these can be provided by existing sensors in the least expensive way?
- How much gain will the WSN provide the farmer in relation to the investment? Measuring the gain in costs saved with improved irrigation and higher quality crops.

1.3 HYPODISSERTATION AND APPROACH

The hypodissertation addressed in this research is:

The current available wireless sensor networks are sufficient and scalable enough to implement commercially in South African agriculture.

To prove this, some thorough research on all related papers about WSNs in viticulture and agriculture was conducted and is discussed in Chapter 2. Commercially available sensor networks will be investigated as well as their relation to current standards. Chapter 3 discusses how the technology assessment was approached. The costs involved in implementing a WSN are documented as well as a projected return on investment. Various wine farmers were surveyed to determine their requirements and needs in precision agriculture, and the outcome of this is presented. A model is provided that can be used with the given requirements and available WSN technologies to determine the most optimum solution for the set circumstances. Finally it will be concluded whether WSNs are sufficient to implement commercially in South Africa.

1.4 RESEARCH GOALS

The overall aim of this research study is to aid the wine farmer in improving crop yield, lowering inset costs and to save water. To achieve this objective, the following goals were set:

- Assess if the trend of research on WSNs is in line with the requirements and solutions provided in the commercial sector.
- Determine the requirements for a WSN implemented in vineyards and derive a model on how to assess the various available technologies.
- Evaluate a suitable commercially available WSN system to determine if the desired requirements have been met and how to further optimise the system.

1.5 RESEARCH CONTRIBUTION

All the necessary hardware and theoretical knowledge exist about the advantages of WSNs. But research still needs to be done and modifications applied where deemed necessary to find the most optimal combination between commercially available WSNs and which architecture and protocols to implement. A contribution will be finding the best available solution, potential improvements thereon and the exposure and implementation of WSNs in the real world, actively starting to use them and thus helping farmers and/or other users in better management of their product.

1.6 OVERVIEW OF STUDY

The following section gives an overview of this dissertation.

- Chapter 2: Literature study

  This chapter reviews the different areas of research done on WSNs. It summarises the key areas of work that have been done on this subject.

- Chapter 3: Methods

  This chapter describes the methodologies followed to assess the WSN technologies as well as how the data was gathered.

- Chapter 4: Results

  This chapter presents the results obtained from the methodologies that were followed and which are described in Chapter 3 from which conclusions are drawn in Chapter 6.

- Chapter 5: Discussion

This chapter discusses and interprets the results presented in Chapter 4.

- Chapter 6: Conclusion

This chapter summarises the research and its results and draws concluding remarks about the work. Recommendations are presented to fulfil the requirements of this work.

CHAPTER 2 LITERATURE STUDY

2.1 INTRODUCTION

Section 1.1.1 stated the context of the problem and a motivation for this research was presented in Section 1.2. A short overview of research done on WSNs was given in Section 1.1.2; this chapter builds on that overview by outlining specific areas related to this research and on which to base any future decisions made during this study. This chapter is comprised of three major topics: wireless sensor networks in general, standards for wireless sensor networks, and precision agriculture with wireless sensor networks.

2.2 WIRELESS SENSOR NETWORKS

Since the beginning of the millennium, WSNs have been a hot topic of research, generating an immense amount of new protocols and algorithms catering specifically for the wireless sensor environment. Due to the wireless channel and scarce resources such as energy for the sensors, existing network architectures and protocols won't suffice. Most scientific publications focus on complicated protocol design which solves generic problems, but few of them report on actual real world applications where simple protocols have been implemented successfully in practice (Raman & Chebrolu, 2008). Five facts have been identified by Tennina *et al.* (2011) as the reasons for limited real world implementations:

- expensive WSN technology,
- unreliable and limited communications,
- limited economical and commercially feasible applications,
- unavailability of established commercially available technology, and
- lack of complete and ready-to-use WSN system architectures.

An additional factor which plays a major role in delaying commercial availability is the struggle to find a suitable standard. Some workgroups like the ZigBee alliance and DASH7 alliance are working to such a goal but with no success yet.

Due to the differences in applications, the network protocols should consider the requirements of the intended application. Some of the research done on the different communication layers specific to WSNs is looked at in the next sections.

2.2.1 Network layers

In wired and wireless networks, the ISO protocol stack has been developed to break down each layer of communication and its functionality. Communication in wireless sensor networks can be based on the following layers (Dargie and Poellabauer 2010; Zheng, 2009):

- physical layer,
- data link layer,
- network layer,
- transport layer, and
- application layer.

However, some of the latest innovations in WSN research are cross-layered protocols, discussed in Section 2.2.1.6, which combine several of the above-mentioned into one layer. A short description of the function of each layer is given next, with some of the current research issues related to their function in a WSN.

2.2.1.1 Physical layer

The physical layer lies closest to the hardware and is responsible for signal generation, encryption and reception, or in other words, it has to convert signals from waveforms into digital bits and vice versa (Karl & Willig, 2007). It has to consider the communication medium, frequency- and carrier signal generation, signal modulation and encoding.

Several different types of wireless communication technologies exist, but two types stand out due their effectiveness, namely radio frequency (RF) and infrared (IR) communication. Optical communications like IR are limited due to their line of sight requirement, but their power requirements make them quite suitable for WSN applications. The main focus for this dissertation was on RF communications. The broadcasting nature of the RF medium, and particularly for WSNs, is asymmetric, or in other words, not all transmission between devices can be at equal rates.

A number of frequency bands are currently used by sensors, but those using the licence-free frequency of 2.4 GHz industrial, scientific and medical band with nearly worldwide availability are the most desirable; however, this band is also used by other IEEE 802 wireless standards. Coexistence is feasible as long as the traffic generated by either device is kept to a minimal and not in immediate proximity (Lansford, Stephens & Nevo, 2001; Howitt & Gutierrez, 2003). Another licence-free frequency band being considered is the 433 MHz band, currently used by the DASH7 standard discussed in Section 2.3.4.

The most important design factors for the physical layer in a WSN, according to Karl and Willig (2007) are:

- low energy consumption which in turn requires small transmit ranges,
- sleeping schedules where the hardware is switched off to save power which causes a low duty cycle and high latency, and
- small, cheap hardware.

These design factors limit the physical layer in its bandwidth and transmission range, and poor packet delivery performance is caused by channel interference, attenuation and multipath scattering (Dargie & Poellabauer, 2010). These limiting factors in turn influence the solutions pursued by researchers for the physical layer which still has room for improvement (Karl & Willig, 2007). However, the IEEE 802.15.4 has adopted the direct sequence spread spectrum (DSSS) technique as its *de facto* standard for WSNs for RF communication and offset quadrature phase shift keying (O-QPSK) for channel modulation (Karapistoli, Pavlidou, Gragopoulos & Tsetsinas, 2010).

2.2.1.2 Data link layer

The data link is responsible for the connections between nodes and the coordination of access times of the node to the shared communication medium (wireless broadcast channel), or in other words, when and in what manner the sensors may speak to each other. It can be divided into three types of responsibilities, medium access control (MAC), flow control and error control.

Medium access control is the primary objective of the data link layer. The main focus of traditional wireless networks for their MAC layer is to improve the throughput and latency; this is however not the main goal in WSNs where low energy consumption is of the highest importance to prolong network lifetime. Research on MAC protocols for WSNs can be classified into three main classes: *reservation*- and *contention-based medium access* and a merger of these two schemes called *hybrid solutions* (Karapistoli, Pavlidou *et al*., 2010). The

MAC protocol implemented by the IEEE 802.15.4 will be discussed in more detail in Section 2.3.1.

Flow control regulates the transmission rate to ensure a node is not overwhelmed by too many data packets, ensuring that packets won't get dropped. The control should be of such a nature so as to avoid collisions, detect errors, lower energy consumption and ensure network throughput with the least amount of latency.

Error control will ensure that the transmission is correct and appropriate actions are taken in case errors occurred. Four types of mechanisms are utilised, forward error corrections (FEC), automatic repeat request (ARQ), power control and hybrid ARQ (HARQ) (Karl & Willig, 2007). The detection of failures in a wireless network is essential (Ruiz-Garcia, Barreiro & Robla, 2008).

2.2.1.3 Network layer

The main function of the network layer is to ensure that a data packet which typically consists of sensor information is routed via the most optimal path towards it destination. Most research has been done on the network layer trying to optimise the routing of data packets. Various routing protocols and techniques will be discussed in Section 2.2.2.

Routing is one of the key technologies in WSNs and is, to a certain extent, application specific. Finding the most optimum generic routing protocol seems to remain a challenge due to the unreliable behaviour of the WSN channel and diverse applications and environments WSNs must work in. An overview of the current routing protocols is given by Goyal and Tripathy (2012) in their paper 'Routing Protocols in Wireless Sensor Networks: A Survey'.

2.2.1.4 Transport layer

The main purpose of the transport layer is to ensure reliable packet delivery in the correct sequence. The transport layer requirements for WSNs differ significantly from the transport layer requirements for the Internet. For WSNs the sensors are aware of their environment and the data they transport but for the Internet it is only viewed as bit streams being transported across. To ensure quality of service (QoS), a lot of overhead is required in checking and resending packets as well as congestion control. This is not ideal for WSNs and poses challenges in designing an optimal transport layer protocol. One such example is given by Akyildiz and Vuran (2010) where, instead of controlling the reliability of each node individually, they can be collectively controlled as a group.

2.2.1.5 Application layer

The application layer is responsible for the interface between the network and the user. It is the top most layer and should be application specific. The user could query the network for specific data, thus causing a request to be sent to the specific node to send the required information. The application layer plays a significant role in the design requirements of the WSN. The differences in the application layer influence how communication protocols are designed; correlation is one example where energy is saved by not sending redundant data.

2.2.1.6 Cross layer

The rapid improvement of the Internet was made possible by the modularised design of the protocol stack and standard interfaces between each layer. However, the communication media of the Internet are not limited like WSNs where energy, processing power and memory are limited. Interdependencies between the layers are caused by the broadcast and non-deterministic nature of the wireless broadcast channel. This motivates the cross-layering of functionalities of several layers into a single logical framework (Akyildiz & Vuran, 2010).

Combining the MAC and transport layer functionalities can already improve the throughput by communicating local congestion to the data sources, thus regulating the input traffic rate. Joining the MAC and network layer, the routing of packets can be coordinated according to the schedule of the nodes' active time. Following the receiver-based routing scheme, instead of waiting for the specified destination node to wake, the packet is routed via sensor nodes that are awake at that moment. The nodes considered for routing are in the most feasible region denoted by A(R,D). The most efficient node is chosen based on a weighted progress factor and transmit power being increased successively as seen in Figure 2.1.

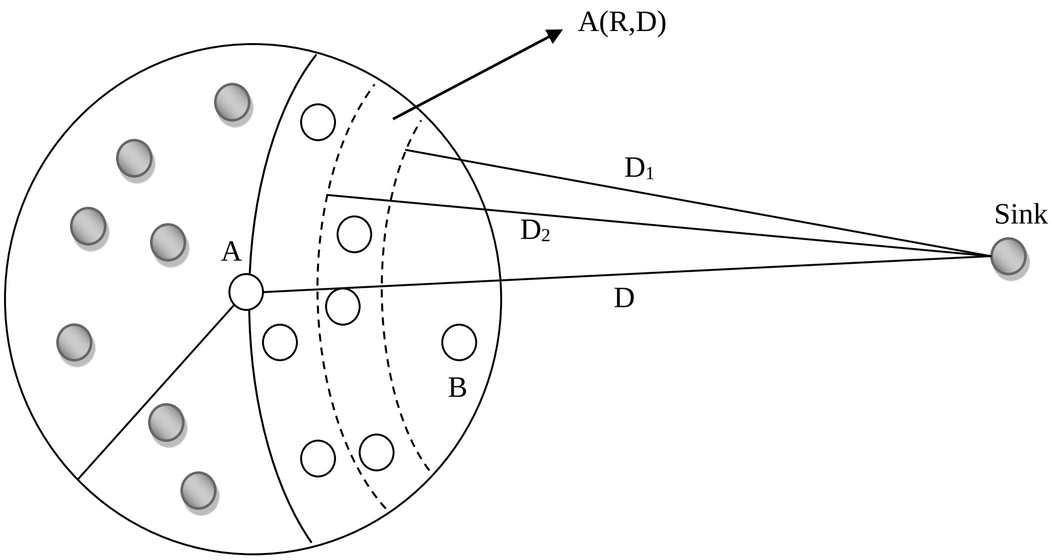

Figure 2.1. Receiver-based routing. Adapted from Akyildiz and Vuran (2010), with permission.

The cross-layer protocol (XLP) as discussed in Akyildiz and Vuran (2010) focuses on the following key concepts:

- Initiative determination
- Transmission initiation
- Receiver contention
- Local cross-layer congestion control
- Angle-based routing
- Channel adaptive operation
- Duty cycle operation.

2.2.2 Protocols

Due to the wide range of applications for WSNs and their various requirements, it will be impossible to find a single protocol and topology suitable for all of them. Node lifetime is the most important variable taken into consideration for WSN protocol designs. Various papers propose new techniques and variations of existing protocols to try and increase the node lifetime by decreasing the battery drain. Singh, Singh and Sing, (2010), Goyal and

Tripathy (2012), Al-Karaki and Kamal (2004) and Akyildiz, Su and Sankarasubramaniam, (2002) provided useful surveys on the characteristics and communication protocols, and classifications, of various protocols shown in Table 2.1 to 2.5 below. Some protocols will fall into several types of classification, depending on the techniques they employ.

2.2.2.1 Location-based protocols

For location-based protocols the sensor nodes are given addresses according to their physical locations and/or relative locations towards each other. A concept of levels is introduced by the Pendulum protocol, describing each node’s number of hops to the sink. The Pendulum protocol reduces the energy consumed by scheduling protocols but requires a high density of nodes to operate effectively (Alsaify & Thompson, 2010). Looking at a tree representation of the nodes according to their locations, their communication schedule is similar to the swing of a pendulum. This approach also requires localisation and time synchronisation, which is still being researched for improvements.

Table 2.1. Location based protocols

MECN	Minimum Energy Communication Network (Rodoplu & Meng, 1999)
SMECN	Small Minimum-Energy Communication Network (Li & Halpern, 2001)
GAF	Geographic Adaptive Fidelity (Xu, Heidemann & Estrin, 2001)
GEAR	Geographic and Energy-Aware Routing (Yu, Govindan & Estring, 2001)
SPAN	An energy-efficient coordination algorithm for topology maintenance in ad hoc wireless networks (Chen, Jamieson, Balakrishnan & Morris, 2001)
TBF	Trajectory-Based Forwarding (Niculescu & Nath, 2003)
BVGF	Bounded Voronoi Greedy Forwarding (Xing, Lu, Pless & Huang, 2004)
GeRaf	Geographic Random Forwarding (Zorzi & Rao, 2003)
MFR	Most Forward within Radius (Stojmenovic & Lin, 1999)
GEDIR	Geographic Distance Routing (Stojmenovic & Lin, 1999)
GOAFR	Greedy Other Adaptive Face Routing (Kuhn, Wattenhofer & Zollinger, 2003)

2.2.2.2 Hierarchical-based protocols

For hierarchical-based protocols the sensor nodes are grouped into clusters. Each cluster has a cluster head that manages the communication within that cluster. Lonbale, Gupta and Bhute (2012) were motivated by the LEACH protocol for their approach of energy aware cluster head (CH) role distribution. The LEACH protocol organises its nodes into clusters where non-cluster head nodes transmit their data to the CH, which in turn aggregates it before sending it to the remote base station. Cluster heads do most of the communication and tend to run out of energy first which causes the region of the network to become disconnected even though the sensors in that region are still active. By distributing the load of the nodes evenly, all the nodes will fail relatively at the same time (Zhou, Cao, Li & Huang, 2010; Lonbale *et al.*, 2012; Morshed & Hossain, 2009).

Two types of sensors are used in a layered approach, one for sensing and one for data transmission. The sensor node only senses data and transmits it to a transmission node (cluster head), which in turns relays the message to the sink. A genetic algorithm is proposed by Zhou *et al.* (2010) to optimise the multicast routing between cluster heads and the sink. This approach could almost double the cost to cover the same area due to two nodes being required. Jia Zhao, Chunming Qiao, Seokhoon Yoon and Sudhaakar (2011) also explored the idea of having sensing nodes and transmission nodes, but took it a step further by reducing the capabilities of the sensing nodes to only sensing and transmitting. This in return reduces the hardware cost due to the removal of unnecessary receiver modules, as well as the energy consumption due to the fact that a typical receiver consumes more energy than that of a transmitter (Jia Zhao *et al.*, 2011; Orndorff, 2004; Shi, 2007). The applicability of CSMA protocols are voided with this approach and little work has been done on it as yet.

Table 2.2. Hierarchical-based protocols

LEACH	Low-Energy Adaptive Clustering Hierarchy (Heinzelman, Chandrakasan & Balakrishnan, 2000)
PEGASIS	Power-Efficient Gathering in Sensor Information Systems (Lindsey & Raghavendra, 2002)
HEED	Hybrid, Energy-Efficient Distributed Clustering (Younis & Fahmy, 2004)
TEEN & APTEEN	Adaptive Threshold sensitive Energy-Efficient sensor Network (Manjeshwar & Agrawal, 2002)
HPAR	Hierarchical Power-aware Routing (Li, Aslam & Rus, 2001)
VGA	Virtual Grid Architecture (Al-Karaki & Al-Mashaqbeh, 2007)
TTDD	Two-Tier Data Dissemination (Ye, Luo, Cheng, Lu & Zhang, 2002)

2.2.2.3 QoS-based protocols

For QoS-based protocols the end-to-end delays are considered during the setup of routing paths. Applications that are extremely performance sensitive, like industrial automation, rely on the time synchronise mesh protocol to deliver a high QoS. According to Pister and Doherty (2008), performance of TSMP's is achieved by:

- a network-wide synchronisation of all the nodes,
- channel hopping between available channels,
- a dedicated, unicast communication bandwidth divided into slots,
- acknowledgement packets (ACKs) on the link-layer,
- graph-based routing, and
- multi-layer security on every packet.

Table 2.3. QoS-based protocols

SAR	Sequential Assignment Routing (Akyildiz *et al.*, 2002)
SPEED	Real time, stateless routing protocol (He, Stankovic, Lu & Abdelzaher, 2003)

2.2.2.4 Data-centric based protocols

For data-centric based protocols the sensor nodes are given addresses according to certain attributes. A query is generated and if the node meets the required attribute it will respond.

For environmental monitoring applications, COUGAR, ACQUIRE and Direct Diffusion have been used (Biradar, Patil, Sawant & Mudholkar, 2009).

Table 2.4. Data-centric based protocols

SPIN	Sensor Protocols for Information Negotiation (Heinzelman, Kulik & Balakrishnan, 1999)
Directed Diffusion	A multipath routing scheme that finds several disjoint paths (Intanagonwiwat, Govindan & Estrin, 2000)
Rumor Routing	Paths are created that are directed towards the events of the encounter (Braginsky & Estrin, 2002)
COUGAR	Tasking sensor networks through declarative queries (Yao & Gehrke, 2002)
ACQUIRE	Active Query Forwarding in Sensor Networks (Sadagopan, Krishnamachari & Helmy, 2003)
EAD	Energy-Aware Data Centric Routing (Boukerche, Cheng & Linus, 2003)

2.2.2.5 Multipath-based protocols

For multipath-based protocols several paths are utilised when communication occurs with the cluster head. The data load is evenly distributed across all paths.

Table 2.5. Multipath-based protocols

Disjoint Paths	Alternate path than primary path with no common sensors (Lindsey, Raghavendra & Sivalingam, 2001)
Braided paths	Partially disjoint path from primary one (Lindsey, Raghavendra & Sivalingam, 2002)
N-to-1 Multipath Discovery	Two phase flooding from sink called branch aware and multipath extension flooding (Chu, Haussecker & Zhao, 2002)

2.2.3 Topology

The performance, as well as each individual protocol's performance, is affected by the network topology (Akyildiz and Vuran, 2010). WSNs are organised into three types of topologies, namely mesh, tree and star or peer-to-peer. In layman's terms, the topology can be described as the locations of the nodes in the network. The layout determines the coverage and connectivity of the network as well as the amount of power required from the nodes to communicate. Topology control is used to manage a node's set of neighbours; the reason for this is to prevent too many nodes linking with each other which places a burden on the MAC protocol, as well as prevents power wastage when nodes try to communicate to neighbours too far away. Three techniques are used for topology control, namely reducing transmission power, forming clusters with cluster heads, and introducing a hierarchical topology.

2.2.4 Architecture

According to Liu (2011), four aspects should be considered for sensor network architecture research. Firstly, the environment-adaptability needs to be addressed and can be characterised as the awareness of the external environment and ability to identify problems and adapt accordingly. Liu (2011) divided the concept into three parts, namely the physical- network- and application-environment where the different parts interact with each other in a cross-layered fashion. The feedback provided from each layer optimises the protocols. Secondly, the network lifetime needs to be maximised. This boils down to increasing the energy efficiency, which in turn is influenced by the network topology, available energy and routing mechanisms. Most energy is spent on communication, but routing is not the only factor to consider. The network topology, data flow, communications interference, and many more factors have an influence on the energy consumption. Thirdly, the architecture needs to be scalable. The network must be able to increase its number of nodes and, irrespective of the environment and size, must maintain its performance and functions. Lastly, the services provided on application level to meet the user needs must be customisable due to the influence the environment has on the upper protocols. This will ensure the network's efficiency and operational capability.

2.3 STANDARDS FOR WIRELESS SENSOR NETWORKS

Flexibility is required due to the rapid improvements that are being made and the differences in application requirements. This flexibility necessitates a unified framework governed by standards (Kiepert & Sin Ming Loo, 2012).

At present, the IEEE 802.15.4 specifies a standard for the physical and MAC layers, but the remaining layers are still varied across applications, researchers and WSN distributors. The

ZigBee standard is the most commonly used on top of the IEEE 802.15.4 standard and defines the network and application layers.

2.3.1 The IEEE 802.15.4 standard

The Institute of Electrical and Electronics Engineers specified this standard in 2003 and later revised it in 2006 (IEEE 802 Working Group 2003; Karapistoli, Pavlidou *et al.*, 2010). It is a specification for the physical radio connectivity between relatively simple devices connected over short distances providing low data rate communication which consumes the minimal amount of energy. The physical and MAC layers are specified by this standard which has the advantage of reliable data transfer with minimal energy costs at a short-range of operation while maintaining a simple and flexible protocol stack. Flexibility is required due to the rapid improvements that are being made and the differences in application requirements. Buratti, Conti, Dardari and Verdone (2009) provided the findings of a survey on the IEEE 802.15.4 (ZigBee) standard, summarised in Table 2.6 below.

Table 2.6. IEEE 802.15.4 physical layer features

Supported frequency bands	**2.4 GHz**	**915 MHz**	**686 MHz**
Number of channels	16	10	1
Data rates	250 kbps	40 kbps	20 kbps
Bit per symbol	4	1	1
Symbol period	16 µs	24 µs	49 µs
Modulation	Offset Quadrature Phase Shift Keying (O-QPSK)	Binary Phase Shift Keying (BPSK)	
Access mode	Sequence Spread Spectrum (DSSS)		
Channel access	Carrier sense multiple access, collision avoidance (CSMA-CA)		
Addressing mode	16 bit and 64 bit		
Features	Radio on/off operation		
	Channel selection		
	Link quality estimation		
	Energy detection		
	Clear channel assessment		
	Automatic network configuration		
	Handshaking		
	Power management		

The IEEE 802.15.4 uses the hybrid method for its MAC layer (Dargie & Poellabauer, 2010; Zheng, 2009) where two types of nodes are defined, reduced function devices (RFDs) and full function devices (FFDs). RFDs are the end devices only capable of performing data gathering tasks with equipped sensors and may only interact with a single FFD. FFDs are network coordinators and can communicate with other FFDs, forming a multihop network. Synchronisation, timeslot management and network joining services are provided by the FFDs. Basic security mechanisms are also implemented by the MAC layer. The star and peer-to-peer network topologies are considered in IEEE 802.15.4. A personal area network (PAN) coordinator allocates channel access to nodes and administrates the network operation. Two modes of PAN operation are supported, with or without a super-frame. Without a super-frame communication happens on the basis of un-slotted CSMA-CA, where the coordinator is always on. End devices periodically wake up and poll the PAN coordinator for pending messages. With a super-frame, seen in Figure 2.2, the coordinator works in two states, active and inactive, where it can go into sleep mode to save energy. A beacon signal is used for synchronisation. Channel access is allocated during the contention access period (CAP) where the nodes compete with a slotted CSMA-CA protocol. Once a node is allocated a channel it can transmit in the contention free period (CFP) with guaranteed time slots (GTS). If the coordinator contains pending messages for a node, it will announce it in the beacon. Nodes sleep most of the time and only wake up periodically to check for pending messages.

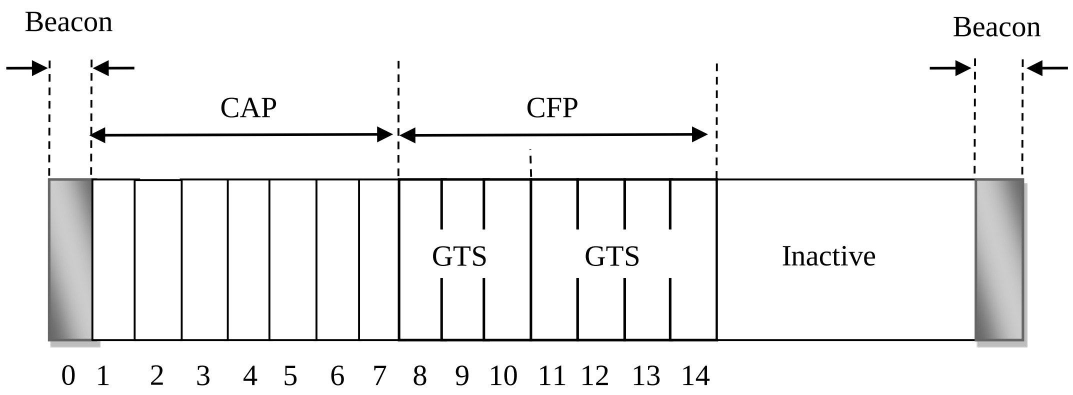

Figure 2.2. MAC super-frame. Adapted from from Baronti, Pillai, Chook, Chessa, Gotta and Hu (2007), with permission.

2.3.2 The ZigBee standard

The ZigBee protocol stack was proposed at the end of 2004 and revised again in 2006 by the ZigBee Alliance, "An association of companies working together to develop standards for reliable, cost-effective, low-power wireless networking" (Zhengand Jamalipour 2009). It is a wireless networking standard used by devices in harsh and isolated radio environments for remote control and sensing tasks. Three types of devices are supported: ZigBee Coordinator, ZigBee Router, and ZigBee End Device. It is expected that ZigBee technology will be the *de facto* standard for a wide range of consumer wireless applications. It builds on the IEEE

802.15.4 standard and defines the network layer for star, tree and peer-to-peer topologies as well as the application layer. A framework is provided by the application layer for specific application programming. Up to 240 user-defined modules called application objects (APO) can be defined for the application layer. An application profile which defines message formats and protocols for interactions between APOs has been defined by the ZigBee Alliance. This allows independent developers to build and sell ZigBee devices that can communicate with each other.

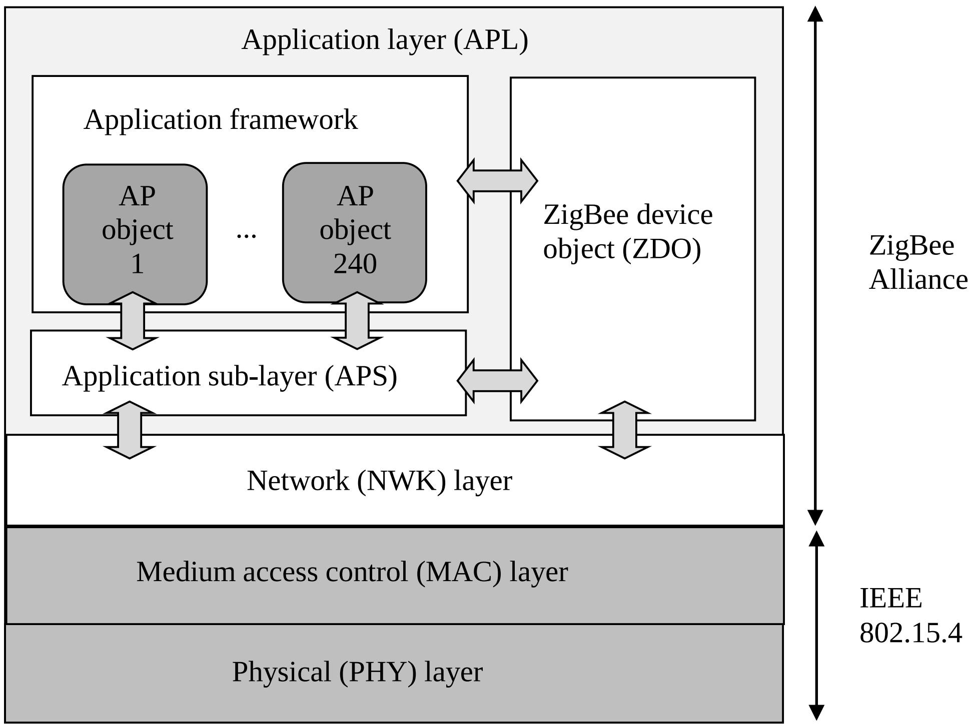

Figure 2.3. ZigBee functional layer architecture and protocol stack. Adapted from Baronti *et al.* (2007), with permission.

In Figure 2.3, taken from Baronti *et al.* (2007), an overview of the ZigBee protocol stack is shown. The network layer provides networking functionalities like routing for different network topologies, such as a multi-hop network. The application layer consists out of several modules, namely the ZigBee device objects which provides services for APO discovery and organisation, the application sub-layer which provides data and security services and the application framework consisting of APOs.

ZigBee has been proved and proposed by various authors as a potential wireless technology in agricultural systems (Baker, 2005; Jedermann, Behrens, Westphal & Lang, 2006; Ruiz García, Barreiro Elorza, Rodríguez-Bermejo & Robla, 2007; Shan, Liu, Prosser & Brown, 2004; Wang *et al.*, 2006). Real time field monitoring, automated irrigation control and monitoring and remote operation of field machinery have all been investigated by Deljoo and Keshtgari (2012).

2.3.3 WirelessHART and ISA-1OO

Industrial applications have strict real-time requirements for process control as well as the necessity for robustness and secure communication due to industrial espionage. ZigBee is more focused on commercial applications and Radmand, Talevski, Petersen and Carlsen, (2010) found that WirelessHART and ISA-100 addressed many of the ZigBee weaknesses. WirelessHART was officially released in September 2007 and added to the IEC standard in 2010, and was designed specifically to meet the industrial application requirements. It is a secure TDMA-based wireless mesh network that operates at the licence-free frequency band of 2.4 GHz. (Lennvall, Svensson & Hekland, 2008; Song, Han, Mok, Chen, Lucas & Nixon, 2008; Khader & Willig, 2013). ISA-100 was created by the Instrumentation, Systems and Automation Society (ISA) and its main focus is coexistence, specifically in industrial applications. Radmand *et al.*, (2010) provide a more detailed comparison between the different standards.

2.3.4 DASH7

DASH7 is built on the ISO/IEC 18000-7 standard which operates in the licence-free 433 MHz frequency band. The DASH7 Alliance was formed as a non-profit consortium to promote this technology. The technology is best suited for bursty, asynchronous communication between devices and requires only a little amount of power to operate. Batteries can last up to years with communication ranges from 250 m up to 5 km and a nominal and maximum data rate of 28 kbps and 200 kbps. The BLAST (bursty, light, asynchronous, transitive) concept is used by DASH7 which makes it ideal for upload-centric, mobile device, networks. In contrary, ZigBee is more suitable for download-centric, static device, networks (Norair, 2009). DASH7 has been stated as a promising technology to be used in agriculture by Piromalis *et al.* (2013) where several key benefits have been listed. The following are the benefits that apply to viticulture:

- Canopy penetration
- Wet plants penetration
- Underground operation
- Long range
- Low power
- Avoid taller than foliage support poles
- Cooperation with RFID tags and readers
- No WiFi and GSM interference
- ISO/IEC 18000-7 Global standard.

Reprinted Table 2.7 with permission from Piromalis *et al.* (2013), shows some of the key features of each WSN technology which highlights the advantages of DASH7 in terms of range and power consumption but its disadvantage of a low data rate.

Table 2.7. Technical features of WSN technologies. Adapted fom Piromalis et al. (2013), with permission.

	DASH7	**ZigBee**	**Low energy Bluetooth**	**WiFi**
Frequency range	433.04 – 434.79 Mhz	2.402 – 2.482 GHz	2.402 - 2.482 GHz	2.402 – 2.482 GHz
Number of channels	1 to 8	16	3	3
Channel bandwidth	0.6 – 1.76 MHz	6 MHz	8 MHz	22 MHz
Nominal data rate	27.8 kbps	250 kbps	1 Mbps	1 Mbps
Max potential data rate	200 kbps	500 kbps	1 Mbps	54 Mbps
Nominal range	250 m	75 m	10 m	25 m
Average power for ten 256-bytes per day	42 μW	414 μW	50 μW	570 μW

2.4 PRECISION AGRICULTURE WITH WIRELESS SENSOR NETWORKS

The concept of precision agriculture has been around for some time now with several research papers published on the topic. With water shortage and demands from a global economy, the need to increase crop yields and quality while using less water and saving on labour costs has become essential (Mareca Hatler, 2008). WSNs could be the answer and are already viewed as enabling technology for precision agriculture. Combining the requirements for precision agriculture with the capabilities of sensor networks has also been implemented successfully, with documented examples in irrigation management, frost prevention and nutrient or pesticides control (Wark, Corke, Sikka, Klingbeil, Guo, Crossman, Valencia, Swain & Bishop-Hurley, 2007). From Blackmore (1994), precision agriculture can be defined as "A comprehensive system designed to optimize agriculture production by carefully tailoring soil and crop management to correspond to the unique condition found in each field while maintaining environmental quality." or in other words, farming where each field is managed separately and intensively.

2.4.1 WSN optimisation techniques for precision agriculture

Different optimisation techniques tailored for agriculture have been investigated by several authors, most of which focus on extending the network lifetime. The farmer has certain requirements that should be addressed and these requirements can be determined by asking the right questions. Does a WSN guarantee a return on investment? How often will the farmer be willing to change node batteries? What type of additional equipment is the farmer willing to purchase for viewing the data, like a tablet or laptop? How many readings per day does the farmer require? What type of information is useful to the farmer? Understanding the requirements of the farmer can also help in improving the communication protocols of the nodes to optimise network performance. Asking the right questions is not the only method required, scientific requirements should also be considered.

2.4.1.1 Sampling rate and data aggregation

Burrell, Brooke and Beckwith (2004) posed the above-mentioned questions and provided some insightful results. Some of their optimisations were where they took sensor readings less frequently during the night and varied the number of readings according to the seasons. Temperature was measured every 60 seconds and stored, then once a day the highest and lowest values could be sent to the sink. This reduces the required traffic significantly for the sensor nodes. They found that designing and configuring sensor networks in vineyards is directly influenced by the work done in the vineyard. For example, workers can be monitored via RFID tags following their progress and keeping track of pesticides being sprayed, or birds can be detected and chased away by an alarm. Beckwith, Teibel and Bowen (2004) did not focus on optimisation but rather on the requirements for accurate data, i.e. the Nyquist frequency. They approached their Nyquist sampling in space and time, placing their nodes not further than 15 metres apart and taking measurements every five minutes. They found that the Nyquist frequencies are dependent on the type of phenomena being monitored.

Zhang Ruirui, Chen Liping, Guo Jianhua, Meng Zhijun and Xu Gang (2010) used data aggregation to limit the number of packets that need to be sent across the wireless link, thus saving in energy consumption.

2.4.1.2 Protocol and topology optimisations

Anurag, Roy, Bandyopadhyay and Kolkata (2008) leveraged the fact that agriculture sensors are not mobile and implemented a routing algorithm based on a static hierarchical architecture. They were able to build up the network relatively fast, based on apriori information, and avoided address wastages caused by the ZigBee C-skip algorithm. By first determining the locations of the sensors, the location of the routers can be optimised. The same technique to plan their topology was used by Lei Xiao and Lejiang Guo (2010). They were also able to use the knowledge of the topology to theoretically determine the fault tolerance capability and bounds on latency. They motivated using a tree topology for planned deployments of sensor networks.

Konstantinos, Apostolos, Panagiotis and George (2007) proposed that to reduce implementation costs an optimal topology can be determined by introducing management zones according to the field characteristics. It is noted that power consumption of the nodes increases due to the wider area of coverage compared to a grid topology with more nodes covering the same area.

2.4.2 Challenges in agriculture for WSNs

The first step in fully utilising the potential a WSN can provide is to thoroughly understand the application domain and how the WSN will function in such a domain. Some of the difficulties in implementing a commercial wireless sensor network have been identified by Camilli, Cugnasca, Saraiva, Hirakawa and Corrêa (2007). Intrinsic details need to be followed to ensure reliable and effective data. Camilli *et al.* (2007), however, predicted that due to ongoing efforts in the WSN field of research and standardisation, this task will become much easier and available to the general user. For irrigation, keeping the soil moisture constant at a certain level is the goal. From Holler (2010) it was found that different locations have different drying rates at different depths. Knowing this can only be determined by analysing the soil and with constant monitoring.

Accessing the WSN via the internet is becoming an essential requirement, but increases the complexity of creating such a system. Another difficult task to achieve is ensuring an adaptable WSN, capable of working in various types of applications. This also adds to the required scalability of the WSN.

An implementation was optimised by Wang *et al.*, (2010) with the L^3SN system by focusing on three difficulty areas. The first difficulty was that farmland is often in the scale of thousands of hectares. This could cause complexities in the network organisation and routing. Thus the large scale has to be considered and catered for. The second difficulty was the requirement for extremely long node lifetimes. Ideally the network should function for several years without changing batteries. The last focus point was the adverse environment in agriculture. The hardware durability will be challenged by the weather and the wireless channel by the growth of crops which interferes with the signal.

Due to the increase in cost when the number of nodes implemented increases, Lei Xiao, Lejiang Guo (2010) stated that the premise of a WSN in agriculture is to design an economically viable deployment mechanism for WSNs that is available to the general user. Ensuring network redundancy and tolerance by increasing the number of nodes must be balanced with the cost of the network.

The following are some more challenges for WSNs in agriculture listed by Ruiz-Garcia *et al.*, (2009):

- The technical knowledge required to maintain the network which farmers don't have.
- Theft of and tampering with the hardware, especially solar panels which are of high value.
- Interference in the radio channel communication due to vegetation growth and weather conditions.
- Overlapping and overcrowding of the unlicensed 2.4 GHz spectrum.

2.4.3 Viticulture with wireless sensor networks

Viticulture is the studying and cultivation of grape vines. Several factors influence the quality of grapes harvested, and it is the job of the viticulturist to ensure that the grapes are of the highest possible standard. Different types of data are required by the viticulturist, but it is important to note that the vine vigour could be used as a general indication of the harvest yield and quality (Hall, Lamb, Holzapfel & Louis, 2002). Monitoring the environmental and soil conditions could be used to construct a spatial variability model of the vineyard which will provide invaluable data to the viticulturist. The conclusion from Beckwith *et al.*, (2004) stated that deploying a dense network helped yielding a better quality crop, and in doing so, proved return on investment. They focused on determining the frequency at which samples should be taken in order to reconstruct the source data. Temperature measurements were taken over a baseline period, giving the "heat unit accumulation". The temperature profiles were used to predict powdery mildew and crop damage due to low temperatures. Camalie Networks started in 2008 to implement a WSN in their vineyard to optimise grape quality while minimising water usage. Their WSN has been field tested successfully and has been in operation for the last eight years (Holler, 2010).

For vineyard specific applications, it has been found that energy harvesting is of crucial importance, as the failure of batteries leads to network failures (Morais, Fernandes, Matos, Serôdio, Ferreira & Reis, 2008). Another suggestion is to introduce an intermediate layer of aggregation nodes, in the form of an intelligent gateway, which manages the sensors. This approach is due to the hierarchical nature of agricultural zones and the distribution of WSNs in these zones (Peres, Fernandes, Morais, Cunha, Lã³pez, Matos, Ferreira & Reis, 2011).

2.5 CONCLUSION

In this chapter, the different network layers have been discussed according to their function in the network as well as technologies developed to support the functions required from the network layer. Various protocols developed were listed to get a grip on the immense amount of research done on this specific topic. The current industry standards, which are an important factor in the roll out of wireless sensor networks in the commercial market, were also discussed. Precision agriculture was looked at next, determining what solutions have been previously implemented and what obstacles have been encountered. Various optimisation techniques investigated were mentioned after which a short overview of precision viticulture was given.

CHAPTER 3 METHODS

3.1 INTRODUCTION

Chapter 2 evaluated previously published work relevant to this research. Sections 1.3 and 1.4 provided the approach and goals for this research. Chapter 3 formalises a methodology on how the research was done to achieve the set goals of assessing the technology. This chapter is comprised of five major topics: technology assessment, interview approach, cost benefit analysis approach, feature approach and finally optimal approach.

3.2 TECHNOLOGY ASSESSMENT

Most research and publications focus on protocol and topology designs, which limits the actual real world, commercially viable applications. Several facts, such as high implementation costs, unreliability, unspecified standards, high profit applications and limited, out of the box, ready to use, systems have been stated as reasons for lack of commercially available sensors (Tennina *et al.*, 2011). Most of the commercial sensor networks mentioned by Tennina *et al.* (2011), like Sensoria, Xsilogy and Tmote Sky have stopped production or even closed down which could be an indication that WSNs are not yet ready for the commercial market. Fortunately, several new providers, as discussed in Chapter 4 (Section 4.2), are available and their respective sensor nodes will be assessed.

The concept of technology assessment (TA) was first developed by the United States Congress as a tool to investigate the social, economic, political, and various other factors that a new technology will impact (Tran & Daim, 2008). In the American industry, TA was adopted as a general guideline, from a business point of view, to assess if the technology is mature enough for production and therefore profitable. This technological readiness approach was taken to do qualitative research to determine if WSNs are ready for commercial agriculture. In Tran and Daim (2008) various techniques of TA have been discussed, but for this research study three techniques were applied, namely surveying (interviews), the cost benefit analysis method and a variation of the mathematical method.

Assessing the technology was divided into two areas, first a commercially available sensor product had to be chosen that meets some standard agricultural requirements. The second area of assessing was according to common needs of viticulturists. Combining these two areas provided a solid model for assessing the technology readiness of WSNs in viticulture. Figure 3.1 shows a flow chart describing the process.

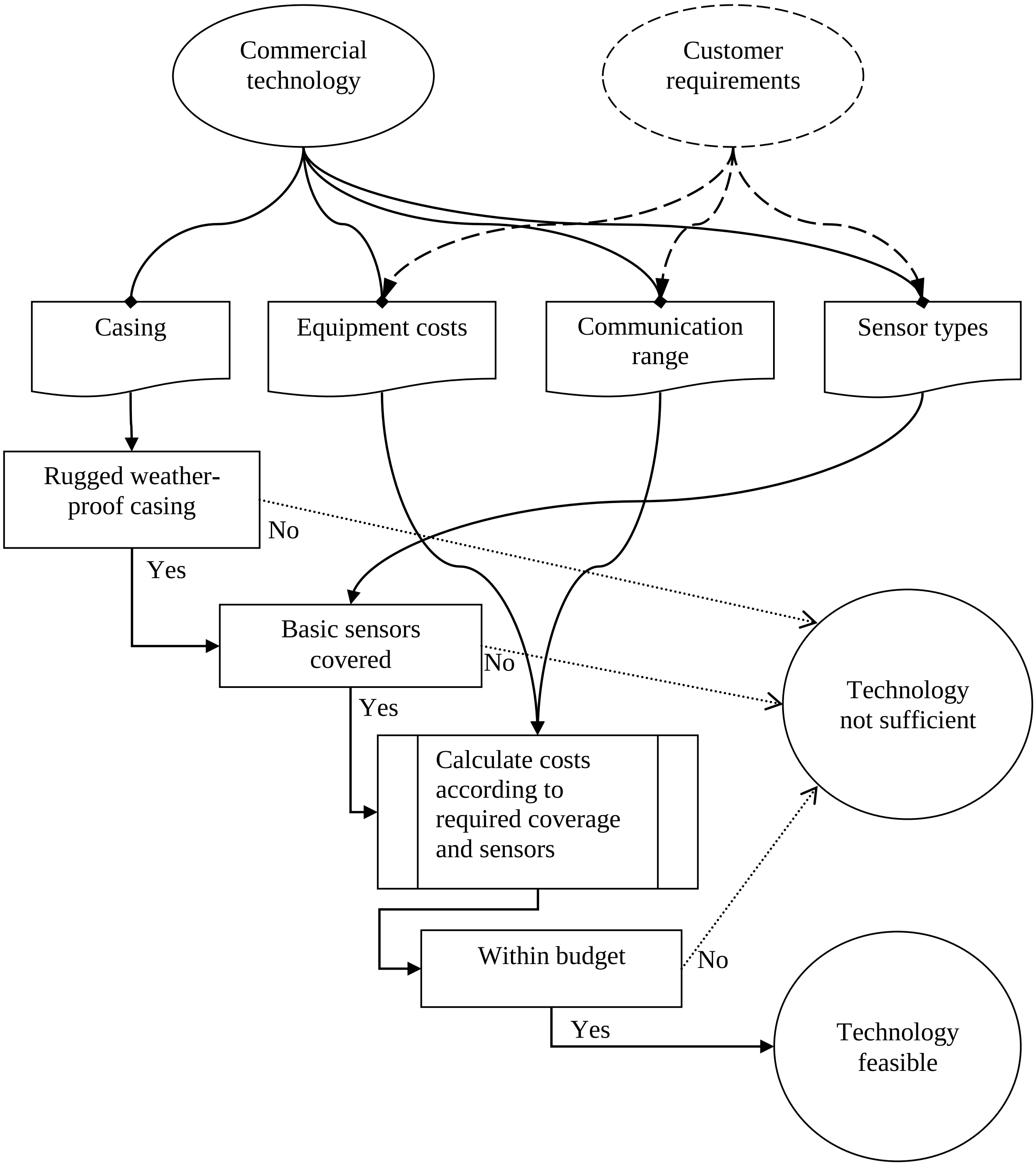

Figure 3.1. TA flow chart

As part of the literature review in Chapter 2, some of the emerging standards related to WSNs were discussed. How the commercial sensors utilise these standards was investigated and is reported in Chapter 4.3 (Section 4.3). This factor has not been included as essential since no standard has been defined yet and research is still ongoing.

3.3 INTERVIEW APPROACH

To obtain a clearer understanding of the needs of farmers for technology in their vineyards, several short interviews were conducted with various farmers. Farmers were chosen that already use sensors in their vineyards to collect environmental data. A number of questions were formulated according to the various factors that influence the sensor network design. These factors and questions are listed next.

3.3.1 Environmental data needed

The type of environmental data the farmer needs will determine the types of sensors required to be added to the wireless nodes. This will typically be data the farmer is already gathering and using to make decisions, but could be better. The following questions were asked to gather information about this topic:

- What technology are you currently utilising?
- Do you feel you are irrigating the optimum required amount?
- Is your weather data gathered frequently enough?
- Would you consider real time data on your crop environment advantageous?

3.3.2 Environmental data desired

Various commercially available agricultural sensor network solutions provide extra types of sensors such as leaf wetness and UV exposure. This will typically be data the farmer knows how to use to better his decision making, but doesn’t have the means to gather the information. Questions asked to gather information about this topic were:

- What information do you feel is lacking and would help in your decision making?
- What information do you consider will help you to produce a better crop?
- Do you monitor pesticide application?

3.3.3 Additional data desired

Various data not related to crop monitoring can be gathered. This will typically be types of data related to monitoring movement and other important areas of interest in the farming process. Questions asked to gather information about this topic were:

- Will monitoring worker and farm equipment movement be of any gain to you?
- Will your warehouse environment data be of any use to you?

3.3.4 Equipment safety

Since not all farms are fenced, equipment safety is an important factor. If the sensor hardware has any possible resell value it will entice theft which will be difficult to prevent in the agriculture sector. Questions asked to gather information about this topic were:

- Do you experience crop theft or vandalism of your vineyards?
- Would you consider any type of technological equipment to be safe?

3.3.5 Available funds

Installing a wireless sensor network could be quite a large investment for a farmer. The farmer must be willing to provide the funds but also be convinced about his return on investment. Questions asked to gather information about this topic were:

- What technology needs do you have?
- Do you consider your decision reaction time according to the weather to be fast enough?
- Do you feel it is possible to increase your crop yield, and how?

3.4 COST BENEFIT ANALYSIS APPROACH

The most important aspect that influences the selection of technology is cost. A major factor for a business man, in this case the farmer, in investing in new technology is his rate on return. The economic or cost benefit analysis (CBA) method is mentioned in Tran and Daim (2008) as one of the most popular research methods used in TA. Several comprehensive approaches have been developed, but for this dissertation a simple, investment costs versus projected return was used to determine if it will be worthwhile to invest in the technology.

The approach followed in estimating the total cost of installing a WSN is discussed next. Various companies who provide sensor network solutions were contacted to gather quotes for their sensor systems. This provided a good idea of what the capital expense will be for installing a WSN. To quantify the benefits, the figures provided by a case study, The tale of two vineyards, done by Camalie Networks (Holler, 2010; Camalie Networks LLC, 2014), was used for estimating the increases achieved in crop yield and savings in irrigation costs.

To further narrow down the capital expense, the number of nodes required (*n*) was estimated by determining the least number of sensors required to ensure the total distance between the sensors in the area the farmer wants to monitor is covered. Here the communication range of the sensor is the determining factor.

The cost of a single node (*C*) is a function of the types of standard sensors (S) and extra features (F) added, plus the cost of the node (*N*) and repeater (*R*),

$$\boldsymbol{C = N + R + f(\mathbf{S}) + f(\mathbf{F})} \tag{3.1}$$

Standard sensors include temperature, humidity and soil moisture sensors of which at least one is included. Some of the specialised sensors (F_z) such as leaf wetness are classified as an extra feature as well as other items such as solar panels. This can then be described as a series sum,

$$\boldsymbol{f(\mathbf{F}) = \sum_{z=1}^{x} F_z} \tag{3.2}$$

The total cost can then be estimated to be a factor of all the sensors plus, where applicable, the cost for the gateway (*G*) and software licensing (*L*),

$$\boldsymbol{C_T \cong nC + G + L}$$

$$\boldsymbol{\cong n(N + R + f(\mathbf{S}) + \sum_{z=1}^{x} F_z) + G + L} \tag{3.3}$$

Some of the costs not considered are sundries required for installation as well as labour costs involved. It is assumed that they will be the same for the different types of commercial WSN technologies and can thus be omitted.

3.5 FEATURE APPROACH

From Tran and Daim (2008), a mathematical model was identified that can be described in four steps:

- Identification of factors that affect the selection of the technology;
- Classification of all identified factors;
- Formulation of a general model in terms of the classification; and
- Quantification of the terms of the model.

Using these steps, a systematic approach was taken. Requirements can be drawn up stating the features the technology should adhere to. A scale of three factors, essential, useful and additional, was used to classify each requirement according to how important it is to be fulfilled. The required features were identified from previous WSN implementations done in vineyards, as well as looking at what factors apply to the specific agriculture domain. The classification of the features was done based on what the results were from the survey that was done. The resulting classified factors were listed and are discussed in Section 4.4. Each available sensor is then evaluated according to these requirements.

3.6 OPTIMAL APPROACH

From the literature study it is evident that the focus on communications protocols has been to optimise them by reducing the node’s power consumption. However, due to standards being set in place for how the sensors should communicate, not much room is left for optimisations with regards to their protocols and therefore optimising various experimental protocols does not form part of the scope of this dissertation. Considering the case study discussed in Section 4.2 and the features identified in Section 4.6, two main criteria were set for implementing a WSN in a South African vineyard. This first was cost and the second, theft. These criteria modelled the final requirement for a WSN and the approach followed in optimising it.

For the ideal WSN, as many nodes as necessary are installed to create a network of hops to connect them all to the base station. However, due to the high cost of sensor nodes, the farmer wants to install the least number of nodes required in the area of interest which will often be one or two nodes. This does not fit in with the approach most WSNs have to create a network of nodes that can route the data. Due to the nature of the communication medium of 2.4 GHz, the vegetation causes interference and line of sight is essential for the nodes to communicate effectively. This makes the field nodes (FNs) visible and a target for thieves. Using repeaters to boost the range of FNs is currently the only solution used. This still remains a setback for current commercial WSNs due to a small number of nodes being deployed. Each node requires a repeater close by to transmit the readings to the base station. This in effect doubles the cost of each node implemented.

Nodes that can communicate further will require fewer repeaters and thus reduce the implementation costs. Using DASH7 as the communication standard was investigated to determine if it provides an optimal solution due to the lower frequency being less affected by the foliage. Nodes were placed on the ground to limit the chances of being seen and stolen. In order to estimate the communication range it is necessary to define the radio propagation model through the foliage. A vineyard was modelled and simulated to compare against the propagation model and actual measured results.

3.6.1 Radio propagation model

Various propagation models suited for outdoor environments exist, but considering the vineyard's characteristics, foliage close to the ground, the most appropriate model would be Weissberger's modified exponential decay (WMED) model (Weissberger, 1982). Weissberger's model was developed to predict the attenuation caused by trees and underbrush and is also used in OMNeT++ and considered as the most appropriate model to simulate WSNs in agriculture. The formula for the model is

$$L_{Weiss}(dB) = \begin{cases} 1.33 f^{0.284} d_f^{0.588}, 14 < d_f \leq 400 \\ 0.45 f^{0.284} d_f, 0 < d_f \leq 14 \end{cases} \quad (3.4)$$

$$L_{Weiss}(dBm) = L_{Weiss}(dB) - 30 \quad (3.5)$$

where L is the losses due to foliage in decibels, f is the transmission frequency in gigahertz and d_f is the foliage depth along the path measured in metres. A graph depicting the model losses at 433 MHz can be seen in Figure 4.11.

3.6.2 Experimental setup

Figure 3.2. WizziMote and base used in signal strength experiments

The WizziMote, of which the default firmware runs the DASH7 physical layer (Michaël, 2015), has been used in an experimental setup to compare to the predicted loss from the WeissBerger model and simulation results. The default firmware of the WizziMotes has a radio test function which provides a link quality metre. This is achieved by three LEDs, green, yellow and red, blinking according to the received signal strength. The motes' default transmission power is +10 dBm (33 mA) with a minimum receiver sensitivity (RSSI) of -110 dBm. Their expected line of sight range, according to the manufacturer, is 600 m. Two omni-directional whip antennas, shown in Figure 3.3, were used in the experiment. Both antennas have a centre frequency at 433 MHz. The small antenna is the ANT-433-CW-RH provided by Linx Technologies.

Figure 3.3. Whip antennas used in experiment

The code was studied to get a more accurate idea of how the blinking frequency is determined in order to interpret the link quality more accurately. The highest measured RSSI is -20 dBm which should cause a constant green LED to be lit. Once the RSSI level goes below -53 dBm the orange LED begins to blink and below -84 dBm the red LED blinks. The blink delay (*D*) in milliseconds was calculated as follows:

$$\boldsymbol{D = 30 + 10 * (R_x - Q(R_x))} \tag{3.6}$$

where

$$\boldsymbol{Q(R_x) = \begin{cases} 84, & R_x > 84 \\ 54, & R_x > 54 \\ 20, & R_x > 20 \end{cases}} \tag{3.7}$$

and $Q(R_x)$ is a function of R_x, the received RSSI level in dBm.

To determine the delay (*D*) in milliseconds from the number of blinks per second (B_s) the following formula was used:

$$\boldsymbol{D = 1000 * \left(\frac{1}{B_s}\right)}. \tag{3.8}$$

R_x can then be determined as follow:

$$\boldsymbol{30 + 10 * \left(R_x - Q(R_x)\right) = 1000 * \left(\frac{1}{B_s}\right)} \tag{3.9}$$

$$\boldsymbol{R_x = 100 * \left(\frac{1}{B_s}\right) - 3 + Q(R_x)} \tag{3.10}$$

Figure 3.4. Vineyard where measurements were taken

Signal strength measurements were taken at the location shown in Figure 3.4. To get a benchmark, the motes were first tested in an open field with no foliage obstructing their line of sight. The results for the benchmark measurements are shown in Figure 4.14. To limit the visibility of the node due to risk of theft, the desired location of it is on the ground, as seen in Figure 3.5. Measurements were taken to compare the performance between nodes placed on the ground (see results in Figure 4.15) using the two different antennas, against nodes placed at the top of the vineyard canopy as seen in Figure 3.6 (see results in Figure 4.16).

Figure 3.5. WizziMote on the ground next to a vine

Figure 3.6. WizziMote placed at the top of the canopy

3.6.2.1 Elevated node

From the measurement results seen in Section 4.7.2, it was evident that the height of the antenna plays a major role in the signal strength. Zhang, He, Liu, Miao, Sun, Liu and Jin, (2012) confirmed this and found that the antenna height has a significant influence on the channel path loss. This can be attributed to the Fresnel zone clearance required for maximum signal strength. Figure 3.7 and Figure 3.8 show the effect of the antenna height on the Fresnel zone (McLarnon 1997) which is defined as:

$$\boldsymbol{F_n = \sqrt{n\lambda\frac{d_1 d_2}{d_1+d_2}}} \tag{3.11}$$

where F_n is the radius in metres of the nth Fresnel zone, d_1 and d_2 are the distances to any point between the endpoints and λ is the wavelength of the transmitted signal in metres. Looking at the first Fresnel zone using $d_1 = d_2$, $D = d_1 + d_2$ and $\lambda = \frac{c}{f}$ the equation can be simplified to

$$\boldsymbol{F_1 = \sqrt{\frac{cD}{4f}}} \tag{3.12}$$

$$\boldsymbol{F_1 = 8.657\sqrt{\frac{D}{f}}} \tag{3.13}$$

where F_1 is the Fresnel zone radius in metres, D the total distance between the nodes in kilometres and *f* the communication frequency in GHz.

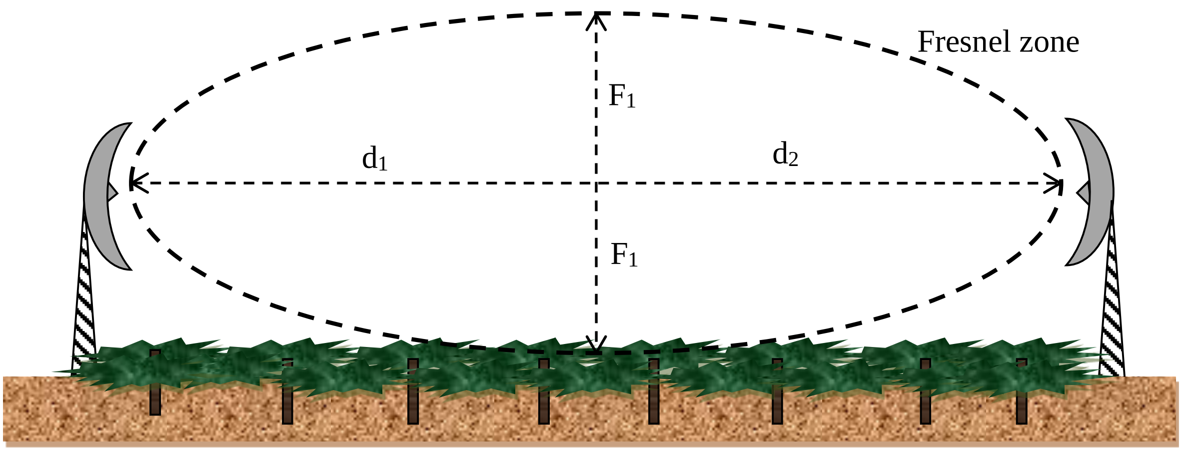

Figure 3.7. Fresnel zone of antennas above foliage

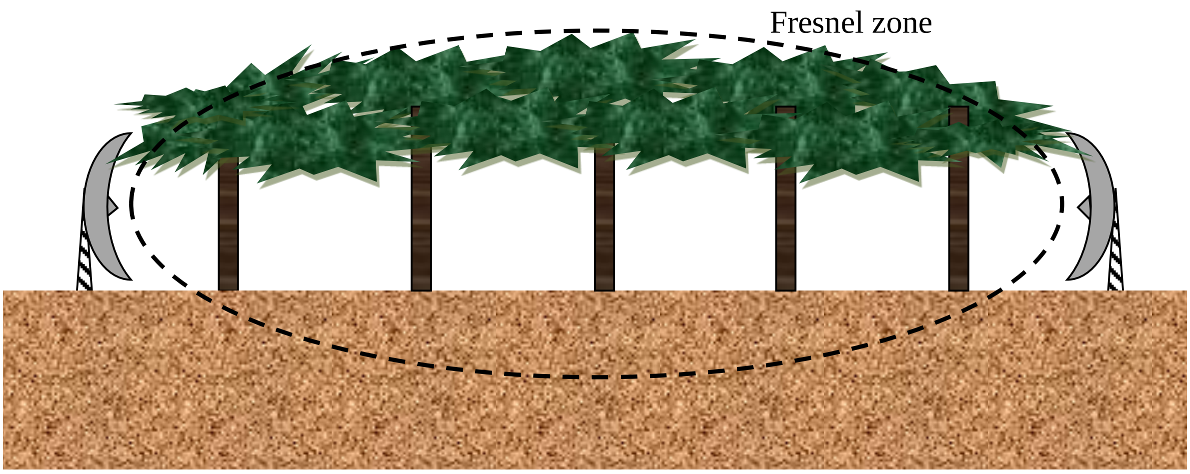

Figure 3.8. Fresnel zone of antennas below foliage

In Valente, Sanz, Barrientos, Cerro, Ribeiro and Rossi (2011), a crop monitoring system using an unmanned aerial vehicle (UAV) has been proposed where the CH node attached to the UAV becomes mobile as depicted in Figure 3.9. They found that the elevated node improves the WSN links.

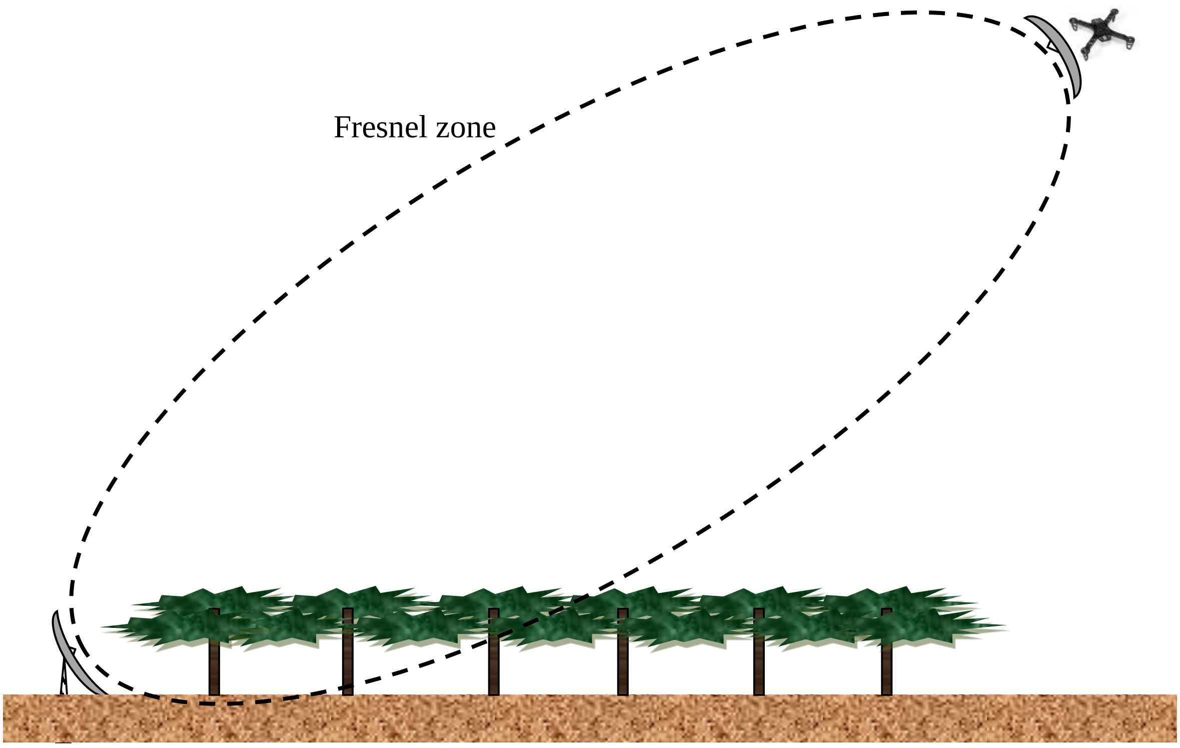

Figure 3.9. Fresnel zone between ground and elevated node attached to UAV

Figure 3.10. Quadcopter used for measurements

Using a quadcopter drone shown in Figure 3.10 and attaching the WizziMote to it, signal strength measurements were taken to determine the maximum communication distance between the nodes as depicted in Figure 3.9.

3.6.3 Simulation setup

From the measurements it was found that the expected communication range had not been achieved. To investigate the reason for this, several simulations were created in FEKO to determine the possible cause of signal degradation. The first simulation was to investigate the characteristics of a quarter wave monopole antenna in a frequency range of 358 MHz – 508 MHz. It was simulated in two environments where the variant factor was the relative ground plane of the antenna. The antenna far field results were calculated. The simulation setup can be seen in Figure 3.11.

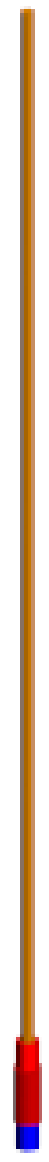

Figure 3.11. Model view for monopole antenna simulation

The second simulation was to try and simulate the Linx whip antenna used in the experimental measurements described in Section 3.6.2. A datasheet giving the antenna characteristics and expected VSWR value of <1.9 at the centre frequency of 433 MHz was used as reference. The antenna casing was removed and the antenna was modelled in CADFEKO as seen in Figure 3.12. The same simulation setup was used as for the monopole antenna above.

Figure 3.12. Linx Technologies antenna simulation model view

The last simulation setup was done where a basic model was created to represent the vineyard (Figure 3.13). Poles was spaced two metres apart with the foliage being represented by a solid dielectric medium at the top. The dielectric constants used for the poles come from Von Hippel (1954) and for the foliage from Chukhlantsev, Shutko and Golovachev, (2003). The Linx whip antenna modelled above was simulated separately in this environment, shown in Figure 3.14, at the single frequency of 433 MHz.

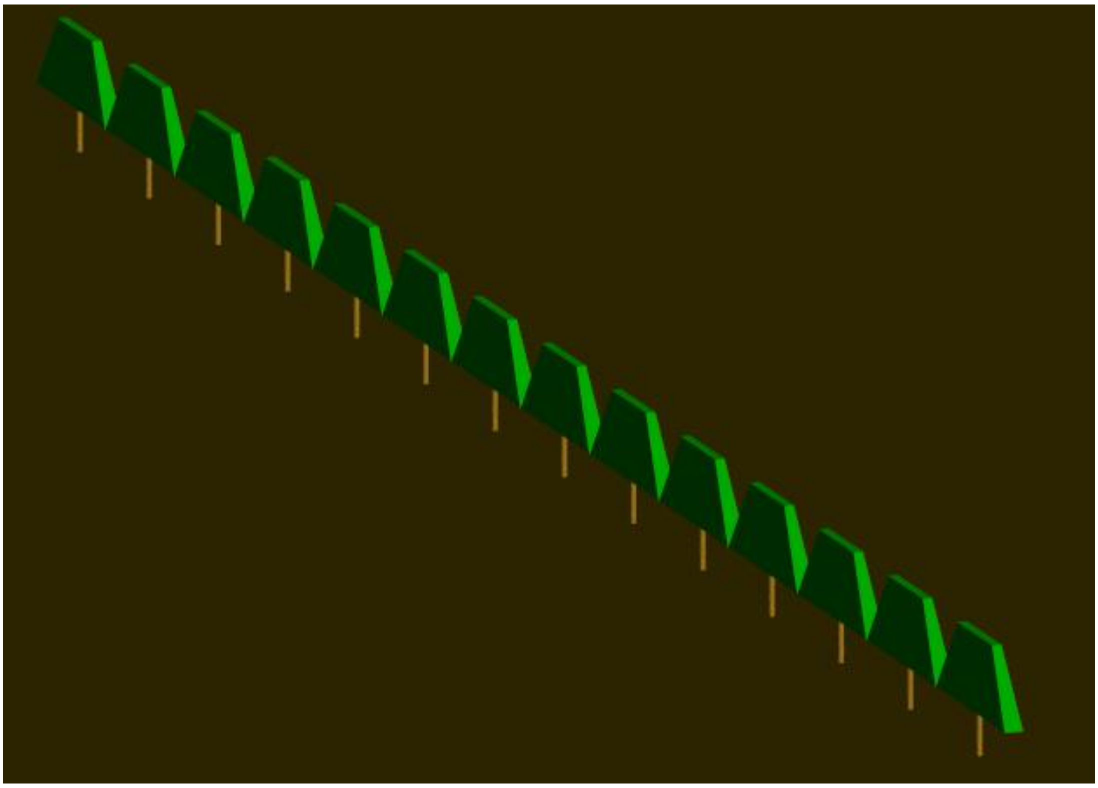

Figure 3.13. Vineyard simulation model

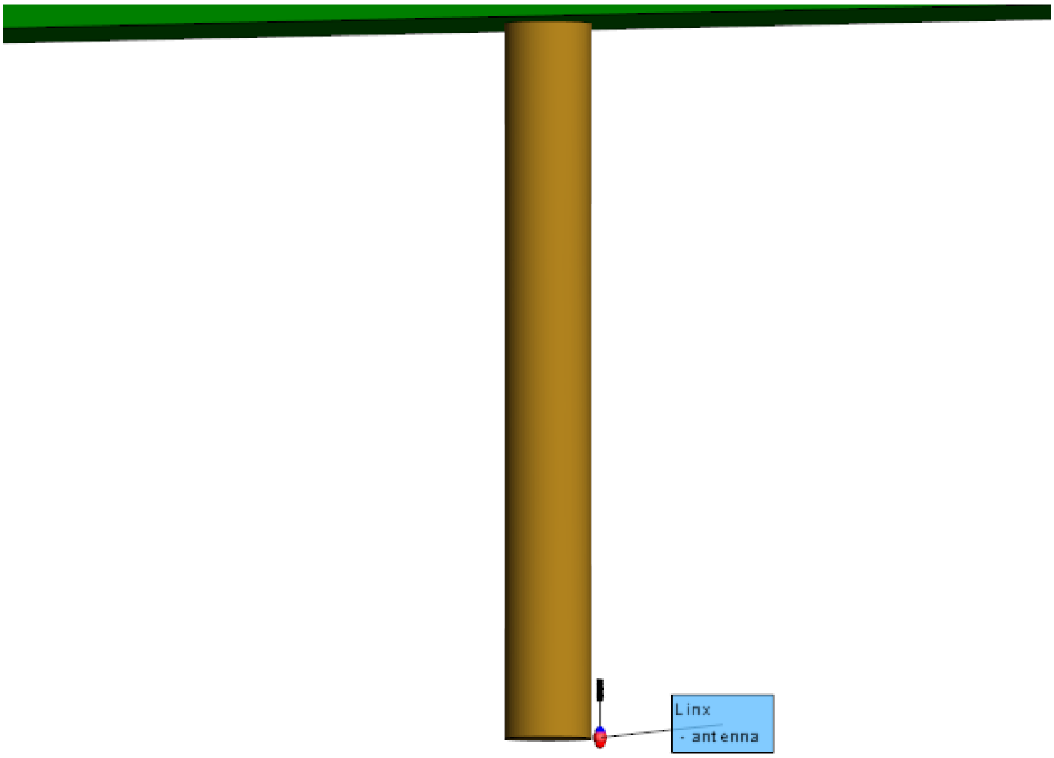

Figure 3.14. Linx whip antenna simulation modelled inside vineyard

3.7 CONCLUSION

This chapter has listed the various approaches that were applied to this research to achieve the desired outcome. A brief introduction on the concept of technology assessment was given, followed by three main techniques used for this research. The needs of farmers for the use of technology in their vineyards were assessed with several short interviews. How the costs and benefits with a list of requirements will be determined was presented together with a mathematical model. Finally, experiments and simulations which had been done to determine the radio signal characteristics of the DASH7 protocol in the applied domain, were presented.

CHAPTER 4 RESULTS

4.1 INTRODUCTION

Chapter 3 described the methodology that was followed for this research and this chapter gives the results obtained. Two main components were described, the first was accessing the technology according to certain criteria given in Sections 3.2 to 3.5 and the second, in Section 3.6, was finding an optimal approach for applying the technology in the domain specified by the criteria identified in Sections 4.2 and 4.6. This chapter's structure is organised to correlate with Chapter 3. First a case study is presented which provided most of the requirements for Sections 3.6 and 4.6. Sections 4.3 to 4.6 report on the results for the various criteria followed in assessing the technology and Section 4.7 gives the measurement results for the optimal approach. Finally, a short conclusion is given leading to the discussion of the results in Chapter 5.

4.2 CASE STUDY

The viticulturist from a wine estate agreed to share their planned implementation of a wireless sensor network. Figure 4.1 shows a Google map's image of the wine farm where the vineyard blocks being fitted with sensors are outlined with red. The total area of vineyards to cover with the sensors will be about 28 hectares. The main office where the base station will be located is marked with an X. The furthest vineyard block from the base station is marked with a G and is about 1.7 km from X. Each block will only be fitted with two to three sensors, due to the fact that irrigation control is limited to the block and cannot be micromanaged. Automatic irrigation was also ruled out due to fear of malfunctioning equipment such as a valve not closing, which could cause considerable damage to the vines. Theft is not a major factor as the farm does have security with an electric fence around the whole estate. The intended system to be installed will be provided by DFM, with a total of 16 sensors. To get maximum coverage by the sensors, their locations will be further apart than each sensor node's maximum communication range of 10 m. A repeater must thus be added at each sensor location, increasing costs.

The most advantageous locations for the sensors were determined by doing an analysis of the ground. Even though only a small area was utilised, more than 40 different types of ground were identified. It was then required to group these types into common factors, and using that outcome, the locations in each block for the sensors were chosen to be where ground types differed the most.

Measuring the soil moisture is the main requirement. Part of the DFM package is software that provides graphs of the logged data as well as notifications when to start and stop irrigation. The number of samples are season dependent, and during the summer season, which is the dry season, daily measurements are required, but for the winter when the vines are resting and it rains, irrigation is turned off and measurements are utilised less frequently.

The system will be deemed over and above worthwhile if a saving of five percent can be made on irrigation. An additional expectation would be that the quality of the crop will increase due to the accurate irrigation of the vines.

Figure 4.1. The Google map's image of wine estate vineyard blocks ©2015 AfriGIS (Pty) Ltd, Google.

During the course of this study the viticulturist changed jobs and moved to another wine farm, resulting in the original planned project being cancelled. At the new farm, which has six vineyard blocks, seven sensors were installed at a cost of R14 000. Due to the risk of theft, wireless nodes couldn't be considered and data loggers were buried in the ground where the data needs to be physically collected once a week. The viticulturist also noted that he is still learning how to interpret the data and control the irrigation accordingly.

The WizziMote signal strength experiment was conducted on this farm shown in Figure 4.2. Location X shows where one node was placed 1 m above ground within the leaves of the vineyard. The signal was lost at location Y, which is uphill from X with vines obstructing the line of site. Location Z, which is the same level as X but with less foliage obstructing the signal still showed a reasonable signal strength of -84 dBm.

Figure 4.2. The Google map's image of second wine farm ©2015 AfriGIS (Pty) Ltd, Google.

4.3 COMMERCIAL WIRELESS SENSOR NETWORKS

Various companies have been found that provide sensor solutions, but not all have suitable products for agriculture. For example, Millennial Net (Millennial Net, 2015) who only focus on indoor industrial and home automation applications and do not cater for the harsh outdoor environment, or Silabs (Silicon Labs, 2015) who provide the wireless chip only, and will require the design and construction of the node. Some offerings are not suitable for South Africa due to their operating frequencies. To name a couple:

- Dust Networks from Linear Technology (Linear Technology Corporation, 2015)
- NI Wireless sensor networks from National Instruments (National Instruments, 2015)

- LD110-AI long range sensor from Wireless Sensors (Wireless Sensors, 2015)

Companies that provide feasible products are discussed and assessed in the following sections.

4.3.1 ēKo^{TM} Pro series

Figure 4.3. ēKo^{TM} Pro node (eN2100) ©2015 MEMSIC, Inc.

This sensor has been used by Camalie vineyards (Holler, 2010) and is one of the first products on the market specialised for agriculture. They are developed in the USA and distributed by a company called Memsic (MEMSIC Powerful Sensing Solutions, 2015) as well as a spinoff company started by Camalie vineyards called Camalie networks LCC (Camalie Networks LLC, 2014) which provide consulting services for installing WSNs in vineyards. Up to four sensors can be connected to the node which is housed in a robust weatherproof casing. A solar panel is embedded which ensures longer operations without having to replace the batteries. Estimated cost is around R5 000 per sensor unit, but is coupled to the exchange rate.

4.3.1.1 XMesh protocol overview

From the XMesh user manual it is specified that they use the IEEE 802.15.4 RF data packet standard with a line of sight communication range around 150 – 300 m between each node. The node uses a custom-developed low-power networking protocol called XMesh. This protocol enables the network to dynamically configure itself, and thus nodes can be added or removed without breaking the network (ad-hoc). No distinction is made between RFDs and FFDs, and each node can forward its own data as well as that of other sensors. XMesh support multi-hop communication allowing various topologies. Nodes automatically discover each other and build up a routing table of all possible radio paths according to the link quality estimates.

Key features of the XMesh protocol are the following:

- TrueMesh

  Nodes are capable of seeking new routes when a part of the network goes down, also referred to as self-organising and self-healing.

- Multiple transport services

  Nodes can send packets to the base station as well as to neighbouring nodes only and the base station can send packets to nodes.

- Multiple quality of service modes

  Two QoS modes can be used, with best effort and guaranteed delivery. The first will send multiple messages to its immediate neighbour and the second will send a message to the base station which in turn sends an acknowledge message back.

- Multiple power modes

  Three different power modes are provided, high power where the motes are always on, low power where the motes are in a sleep state and wake periodically to communicate, and extended low power which is only used for end nodes that cannot route data.

- Health diagnostics

  Each node can report its health information such as power levels and network performance to the base station.

- Time synchronisation

  The global mesh network can be synchronised to ±1 msec.

- Over the air programming

  Nodes in the mesh can be reprogrammed over the air. Different codes can be sent to different motes.

4.3.2 Waspmote Plug and Sense!

Figure 4.4. Waspmote Plug and Sense! node ©2015 Libelium Comunicaciones Distribuidas S.L.

These WSN nodes are being developed and supplied by a company called Libelium (Libelium, 2015), located in Spain. At the moment they seem to be at the forefront of technology, with a modular design capable of various application domains. The node is housed in a robust weatherproof casing, with an optional solar panel extension to improve battery lifetime. It has six connectors to which sensors can easily be attached. Estimated cost is around R6 000 for the sensor unit and R10 000 for the base station. Several external cloud services can be used as management software which requires yearly subscriptions. Each node can be equipped with up to seven different radio modules. The protocols of interest they provide are the XBee-ZB and DigiMesh protocols, of which the latter use the least amount of power and provide a line of sight communication range of up to 7 km.

4.3.2.1 XBee-ZB protocol overview

The ZigBee-PRO v2007 standard is used and extended by XBee-ZB with certain functionalities such as node discovery and duplicate packet detection.

A coordinator assigns a 16 bit network address and a PAN ID, as well as the channel that the network will use. For ZigBee-Pro, 13 channels are available and once the network is active the channel cannot be changed. Two topologies, namely star and tree, are supported by ZigBee.

ZigBee supports two transmission methods, namely broadcast, which should be used sparingly, and unicast.

Routing is done using mesh routing based on the ad hoc on demand distance vector routing (AODV) protocol. Each device has a unique 64 bit address used to identify it. When the device joins a network, it is assigned a 16 bit network address. Transmissions are done on this 16 bit network address, but due to the non-permanent nature of this address, it first has to be discovered by using the unique 64 bit address. To initiate communication, the device must broadcast the unique address, where the corresponding node will respond with its network address. QoS is ensured by ZigBee with ACK packets on both the MAC and application support (APS) layer. On the MAC layer data ACK packets are sent between each node the packet travels and data will be retransmitted up to four times if no ACK is received. On the APS layer a response is expected from the destination device. The ACK packet traverses the same path as the data packet and will be retransmitted up to two times if no response is received. The following are the key features of the XBee-ZB protocol:

- Node discovery

  Nodes on the same network can be discovered by using extra information added to the packet headers.

- Duplicated packet detection

  This ensures that packets are not aimlessly and repeatedly sent around the network.

- Encryption

  Advanced encryption standard (AES) with 128 bit key is used.

4.3.2.2 DigiMesh protocol overview

The DigiMesh protocol has been developed to allow mesh networks where all nodes work on equal terms and router nodes which have to be on permanently are not required. Key features of the DigiMesh protocol are the following:

- Self-healing

  Nodes can join and leave the network ad-hoc.

- P2P architecture

  All nodes are equal, there is no differentiation between FFD and RFD.

- Silent protocol

AODV routing where communication is only initialised on demand.

- Route discovery

Routes are discovered dynamically and not kept in a route map.

- Sleep modes

Modes are synchronised to wake up at the same time.

4.3.3 ENV-Link™-Mini-LXRS®

Figure 4.5. ENV-Link™-Mini-LXRS® node ©2015 LORD MicroStrain®

These sensors are produced by a company in the USA called MicroStrain (LORD Corporation, 2015) and are designed for the harsh outdoor environment. The product can accommodate three 0-5 VDC sensors and a relative humidity/temperature sensor. A South African company (ESTEQ) distributes their products locally and the nodes cost about R7 000 and the routers R18 000.

4.3.3.1 LXRS™ protocol overview

They use the IEEE 802.15.4 communication standard at the 2.4 GHz frequency spectrum, with a combined communication distance between several line of sight nodes to the base station of up to 2 km. The network system uses a lossless extended range synchronised (LXRS™) networking protocol (MicroStrain® Sensing Systems, 2015). A TDMA-based beaconing protocol is used to synchronise each node and build up a structure used by the base to control communication with the child nodes. A beacon is sent out from the WSDA®-Base each second. Once a node receives the beacon it will synchronise and time stamp its data and send it to the base. If no beacon is found, the node will go into sleep mode waking every two minutes to check for a beacon signal. When the node sends data to the base, it will send an acknowledgement if there were no errors. The node will retransmit its data if it doesn't receive the acknowledgement, ensuring QoS. This protocol is fairly effective in that each node only communicates in its allocated time slot, reducing network contention and power consumption due to collisions. The disadvantage is that the whole network will have to be reconfigured when adding nodes due to the TDMA time slot structure. Key features of the LXRS™ protocol are:

- packet delivery success rate of 100 percent due to the lossless wireless communications protocols;
- extended range by linking nodes of up to two km;
- various sampling modes for scalability (continuous, burst and hybrid); and
- nodes synchronised at ±32 microseconds.

4.3.4 HOBO® node

Figure 4.6. HOBO® node ©1996-2012 Onset Computer Corporation

These sensors are the most basic commercial solution found and are provided by a company in the USA called Onset (Onset HOBO® Data Loggers, 2015). Only the essential types of sensors, such as soil moisture and temperature sensors are supported. They are much cheaper than the other options with nodes costing around R4000 and the routers around R3 500.

4.3.4.1 HOBOnode protocol

They use the IEEE 802.15.4 communication standard with a limited line of sight range of around 100 to 300 m, and have to make use of repeaters to extend it to about 1.6 km.

A time slot-based protocol is used where the network is preconfigured and each node gets a slot to send its data in. The HOBOnode receiver assigns the slots to the nodes within its network. The slot length is one minute, which means that it will take one minute for each hop the data packet has to travel through. Each HOBOnode sensor will take measurements at the start of the one minute cycle and send its data in its allocated time slot. QoS is ensured by ACK packets for each transmission. If no ACK packet is received, transmission will be retried up to four times. Once no successful communication has been made, the node goes into a ‘lost’ state. The HOBOnode receiver will search for ‘lost’ nodes once every hour, and if reconnection cannot be established the search will move down the hierarchy of repeaters until the node can be found. This allows for nodes to be moved, but adding new nodes will require the network to be reconfigured. A maximum of four repeaters can be connected in series and a network can consist of up to 50 nodes and repeaters. Key features of the HOBOnode protocol are:

- unique network IDs allows for separate networks in the same area, and
- repeaters increase the communication range.

4.3.5 Continuous logging soil moisture probe (CLSMP)

Figure 4.7. DFM continuous logging soil moisture central radio, repeater and probe ©2015 DFM Software

A local designed WSN system is provided by a company called DFM Software solutions which started in 2000 (DFM Software Solutions, 2015). Their main focus is highly specialised end-user applications for agricultural markets, but their data logging system launched in 2005 is applauded as the most effective system locally available with more than 28 000 probes installed. The sensors communicate in the licensed 868 /915 kHz frequency bands and have a battery life expectancy of two years. Unfortunately they do not make use of any of the current developing communication standards. The probe’s communication range is less than 10 m and has to be in range of the repeater which has a line of sight range of up to 1.2 km. The sensors are the most affordable at around R2 900 per node and R3 500 for the repeater, which most likely contributes to their widespread use.

4.4 SURVEY RESULTS

An internet search was done for wine farms in the Boland area currently using technology in their vineyards. The following viticulturists agreed to be interviewed:

- Guillaume Nel, Cavalli Estate

- Bob Hobson, Morgenster
- Drikus Heyns and Isabel Habets, Distell.

4.4.1 Significant factors

Two major factors, with regards to their requirements for a WSN in their vineyard, were significant to all the wine farmers interviewed:

- cost, and
- support.

For some farmers theft was also an important factor to consider due to limited security for their vineyards and previous incidents of theft. How the sensors integrate with existing equipment like irrigation pumps was noted, but not as an essential requirement. Since farming equipment has several years' lifetime, the expected lifetime for WSNs has also been noted to be around 15 years. Current systems being utilised consist of data logging capacitor probes that measure the soil moisture. The main advantage of using such a system is the low cost required to implement it and the maintenance provided. Turnaround time for data in the vineyards can be more than five days, which makes these types of sensors practical.

4.4.2 Prospective requirements

Not all data gathering methods used by viticulturists are mechanised yet and still have to be done by hand. The Spectron™ gun (Vine Tech Equipment, 2015) is an example where the grape maturity can be measured in a non-invasive manner. Another useful type of data, the Normalized Difference Vegetation Index (NDVI), can only be gathered with aerial photography where drones were mentioned as a prospective tool. Tracking the yield of each harvest has been noted as desired.

4.5 COST BENEFIT ANALYSIS

The approximate costs for each commercially available sensor system are shown in Table 4.1. These values were obtained from quotes received for the various WSN technologies. Some of the quotes were provided in US dollars or Euros and were converted and rounded to Rand. For the zero cost values either the part does not form part of the system or is already included without additional costs.

Table 4.1. Sensor system costs

	ēKo™ Pro Series	**Waspmote Plug and Sense**	**ENV-Link™ Mini-LXRS®**	**HOBOnode**	**CLSMP**
Node	R 5,100	R 6,000	R 7,200	R 1,550	R 0
Repeater	R 3,500	R 0	R 0	R 1,900	R 3,500
Gateway	R 10,000	R 10,000	R 18,000	R 0	R 0
Software	R 0	R 0	R 0	R 1,050	R 2,000
Sensor cost	R 1,100	R 730	R 0	R 2,600	R 2,900

Table 4.2. Sensor systems range

	ēKo™ Pro Series	**Waspmote Plug and Sense**	**ENV-Link™ Mini-LXRS®**	**HOBOnode**	**CLSMP**
Maximum optimal range (m)	300	7000	2000	1600	1200
Minimum[1] range (m)	60	1400	400	320	240

4.5.1 Minimal WSN system costs

Using the figures from Table 4.1 and the equation from Section 3.3, the following estimation graph can be drawn up comparing how much a WSN system consisting of four sensors costs. The cost ranges from R25 000 up to R49 000.

[1] Assumed an 80% reduction in distance due to canopy interference with the signal strength.

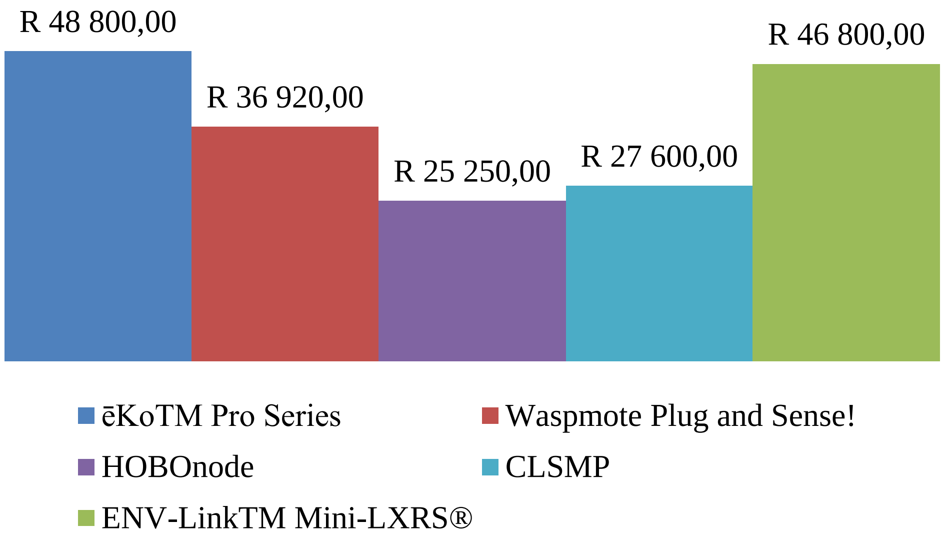

Figure 4.8. Cost estimation

4.5.2 Cost growth relevant to coverage distance

Placing the minimal sensor system of four nodes in series, the total distance they can communicate is plotted in Figure 4.9. The range between the various sensors lies between 1.2 km up to 28 km and using this range and the cost estimation for the network, the cost per kilometre can be calculated as shown in Figure 4.10. The difference is quite significant between the cheapest system of R1 3000 per kilometre, and the most expensive system of over R40 000 per kilometre.

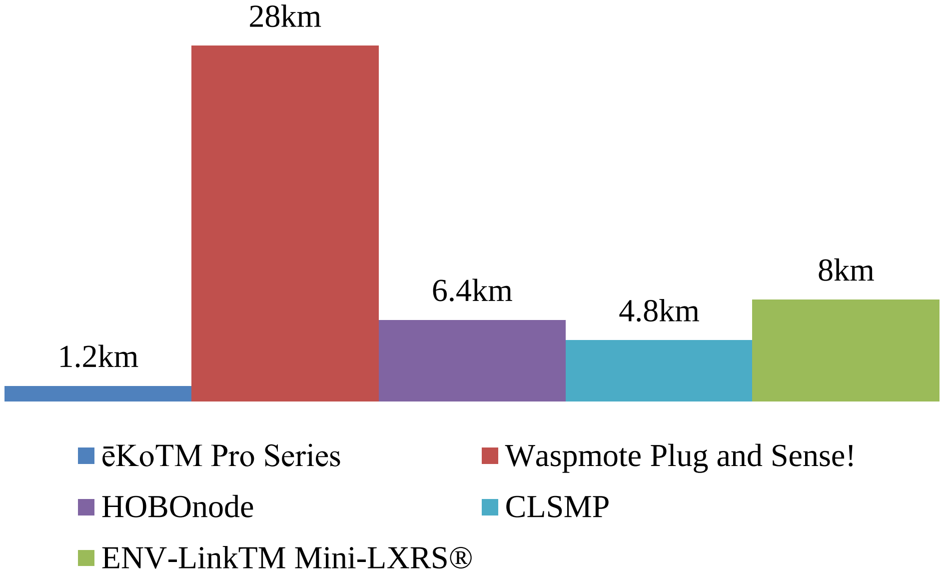

Figure 4.9. Minimum distance covered by four node network

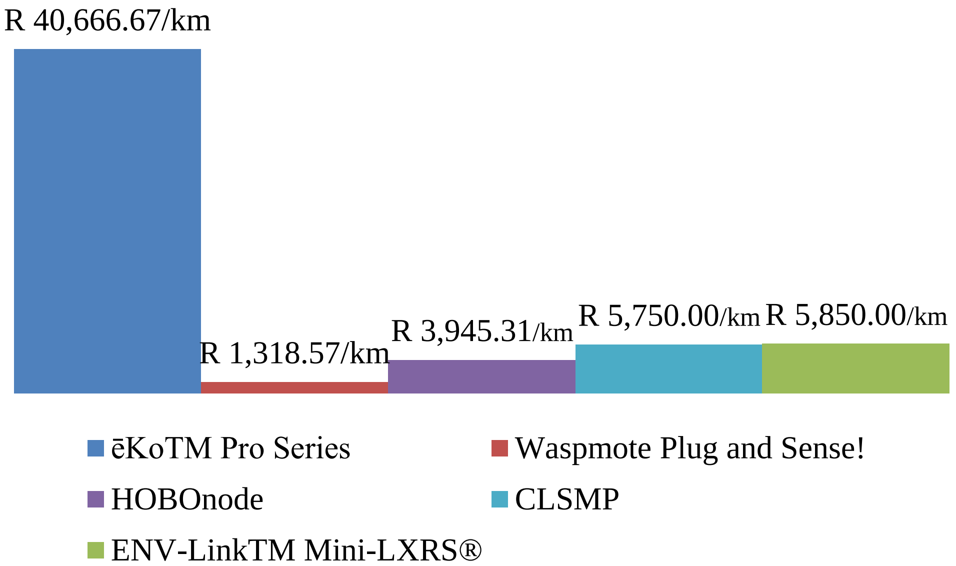

Figure 4.10. Cost per kilometre of communication

Estimating the cost of implementing a system for the case study mentioned in Section 4.2 is shown in Table 4.3 below at R56 600. The actual benefit in rand value could not be estimated, but using percentages achieved by Holler (2010) a predicted saving of around 50 percent can be achieved on current expenses.

Table 4.3. Relative benefit compared to estimated cost

Costs		**Benefit**	
Sensors	R41 600	Increased crop yield[2]	56%
Installation costs	R8 000	Reduced water usage from irrigation control[3]	50%
Software training	R2 000	Reduced power usage from irrigation control[4]	50%
Maintenance	R5 000		
Total	R56 600		

[2] Actual value achieved by Holler (2010).

[3] Actual value achieved by viticulturist from the case study in Section 4.2.

[4] Value is directly proportional to reduced irrigation due to pumps working less.

4.6 IDENTIFIED FEATURES

Table 4.4 lists the identified features the WSN must adhere to and which will be discussed in order of importance.

Table 4.4. The factors identified that commercial sensors should adhere to

Requirement	**Sensor result**
Range > 1 km	✓/✗
Communication encryption	✓/✗
Standard communication protocols	✓/✗
Battery lifetime > 1 year	✓/✗
Solar panel	✓/✗
Robust weatherproof casing	✓/✗
Extendable sensor board	✓/✗
Local support	✓/✗
Management software	✓/✗
Weather station	✓/✗
Soil moisture sensor	✓/✗
Soil temperature sensor	✓/✗
Temperature sensor	✓/✗
Humidity sensor	✓/✗
Leaf wetness sensor	✓/✗
Atmospheric pressure sensor	✓/✗
Luminosity sensor	✓/✗
Trunk/Stem diameter sensor	✓/✗
Solar/UV radiation sensor	✓/✗

4.6.1 Essential factors

The most important factor that influences the selection of technology is cost. The cost of implementing a WSN can be divided into two main parts, the installation and maintenance costs. For installation, each sensor unit's cost will be dependent on the types of sensors attached and any additional features such as solar panels. A factor which have a relative influence on the cost is the range of the sensors; the bigger the range, the fewer sensors will be required, thus, the lower the costs. This is important for the farmer as it will determine how many sensors can be deployed with the available budget. The basic sensing types such as temperature and soil moisture are also a must-have as this is the most valuable information the farmer requires. The sensor must also be in a robust weatherproof casing and for typical farmers in Southern Africa, have no incentive for recycle value due to risks of theft. This also increases the importance of battery lifetime, due the risk of theft by using solar panels, the farmer has to rely on using batteries only, which should last at least one season (1 year). It is clear that current farming practices have great scope for sensors gathering environmental information, but due to expert knowledge being required to interpret various complex measurements, the desired systems need to be minimal and easy to understand. Software that interprets the data gathered is an important factor for the farmer. Lastly, the system must have local support due to the technical complexity of maintaining the system as well as the lower costs compared to imported systems.

4.6.2 Useful factors

The second set of requirements can be classified as somewhat important, but not crucial. Installing a weather station in the WSN will provide localised accurate weather data and will be of great assistance to the farmer. Adding humidity sensors as well as soil temperature sensors can also provide additional data to the farmer to help in decision making. An extendable sensor board will enable the farmer to add even more different types of sensors and increase the lifetime of the technology by enabling the system to be upgraded as new sensors become available. Using standard communication protocols also helps with the extendibility of the WSN as other types of nodes that use the same communication protocols can be added to the network. The threat of stealing or hacking the data sent over the network is low due to the remote locations of most farms as well the type of data being sent, which lowers the need for encryption.

4.6.3 Additional factors

The last group of the least important requirements can be classified as nice to haves. These are basically more particular types of sensors and due to the specialised knowledge required to interpret their readings into meaningful actions, they are not considered to be essential. Typical sensors that fall in this category are leaf wetness, atmospheric pressure, trunk/stem diameter and solar/UV radiation sensors.

Table 4.5. The results from the evaluated sensors

		Essential						**Useful**							**Additional**				
	Local support	Range > 1 km	Robust weatherproof casing	Battery lifetime > 1 year	Soil moisture sensor	Temperature sensor	Management software	Weather station	Solar panel	Soil temperature sensor	Humidity sensor	Extendable sensor board	Communication encryption	Standard communication protocols	Leaf wetness sensor	Atmospheric pressure sensor	Luminosity sensor	Trunk/Stem diameter sensor	Solar/UV radiation sensor
ēKo™ Pro Series	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✗	✓	✗	✓
Waspmote Plug and Sense!	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
ENV-Link™ Mini-LXRS®	✓	✓	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✗	✓	✓	✓	✗	✗
HOBO® node	✓	✗	✓	✗	✓	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
CLSMP	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✗	✓	✗	✗	✗	✗	✗	✗

4.7 OPTIMAL DESIGN INVESTIGATIONS

The identified criteria of cost and theft influenced the design to optimise the WSN. The nodes were placed on the ground, out of sight, to minimise chances of theft. This influenced the second criteria to save costs by using fewer nodes because the communication distance between nodes decreased. To improve the communication distance, the CH node's height was increased by attaching it to a quadcopter to investigate whether the effects of scattering, due to the node close to the ground and not meeting the required Fresnel zone clearance, could be mitigated. The results of the methodology followed are reported next.

4.7.1 Propagation model

Using the formulas given in Sections 3.4 and 3.5 at a frequency of 433 MHz, which is the operation frequency of the WizziMotes and specified by the DASH7 standard, the WMED model can be solved. The results are plotted in Figure 4.11 below and converted to dBm in Figure 4.12 by subtracting 30 dB. At a distance of 600 m a signal loss of -45 dB or -75 dBm is expected.

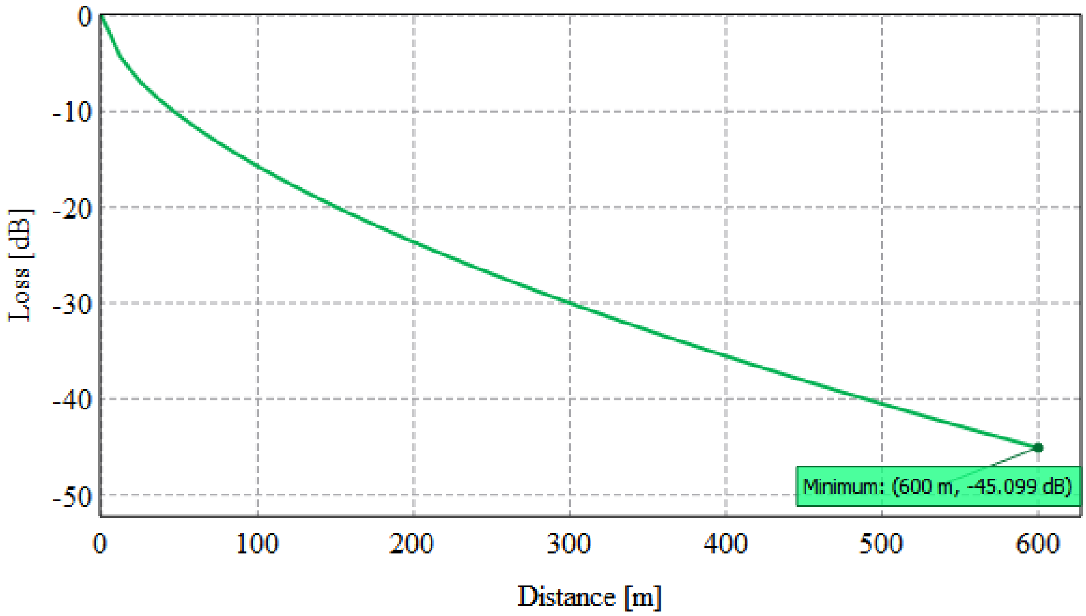

Figure 4.11. WMED model at 433 MHz results

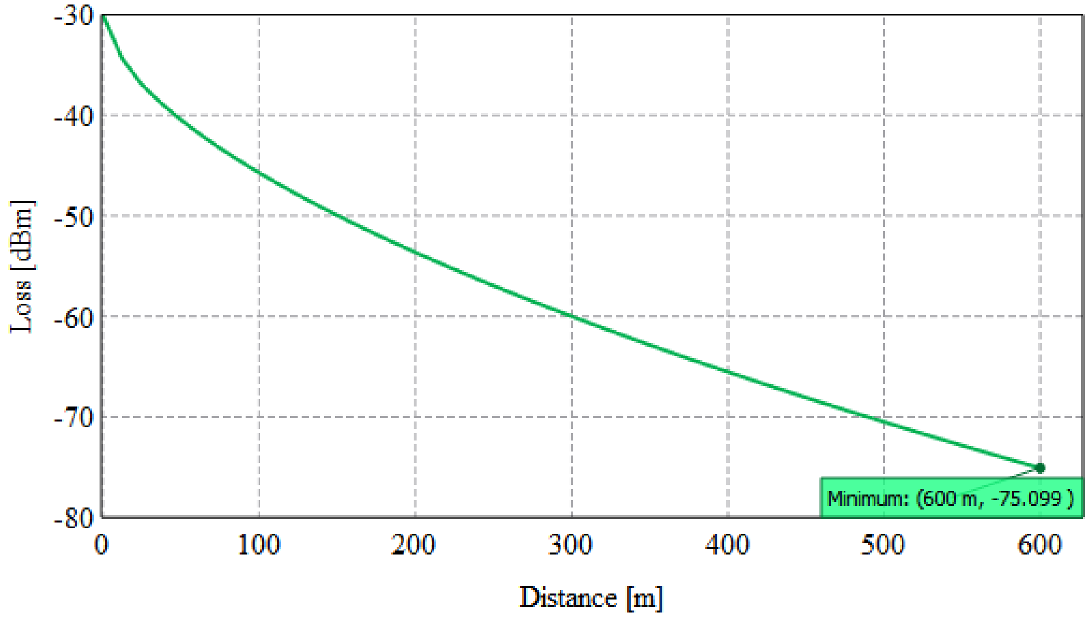

Figure 4.12. WMED converted to dBm

4.7.2 Required Fresnel zone

Using the equation specified in Section 3.12 where f = 0.433 GHz, the first Fresnel zone and the required 60 percent clearance over distance are depicted below. At a distance of 600 m the required Fresnel zone with 60 percent clearance is 6 m.

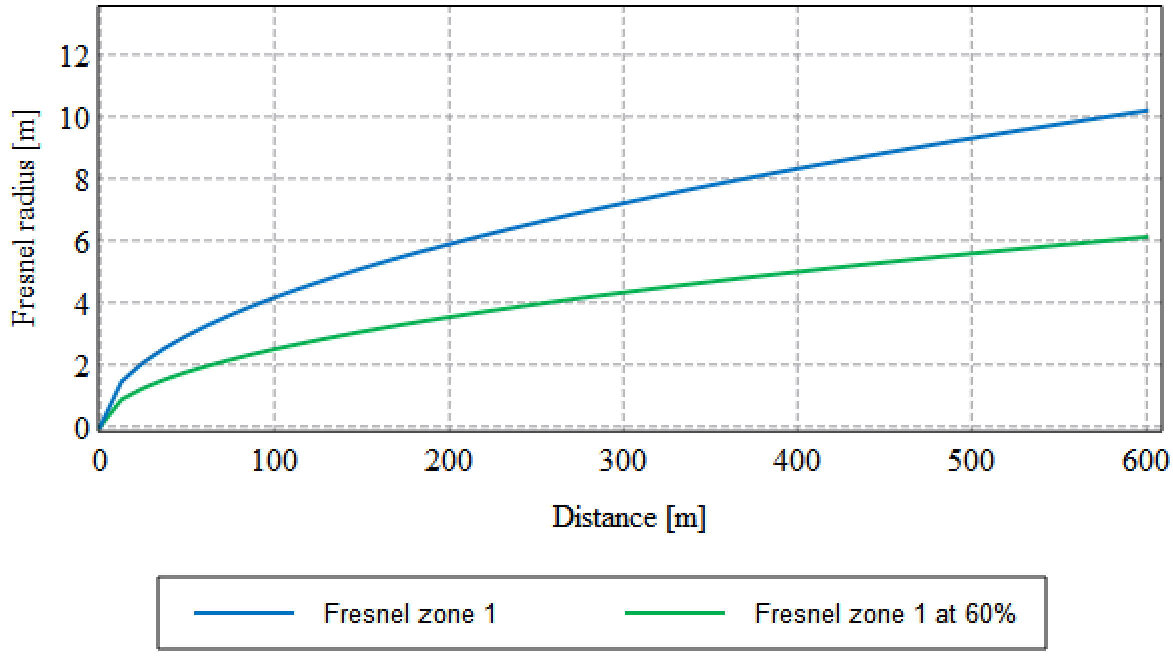

Figure 4.13. First Fresnel zone with required 60 percent clearance

4.7.3 Signal strength measurement results

Benchmark measurements taken in an open field are shown in Figure 4.14. The signal strength of the monopole antenna goes below -100 dBm at 70 m when the nodes are not in line of sight of each other. For nodes in line of sight, a signal strength of -85 dBm was measured at a distance of 110 m.

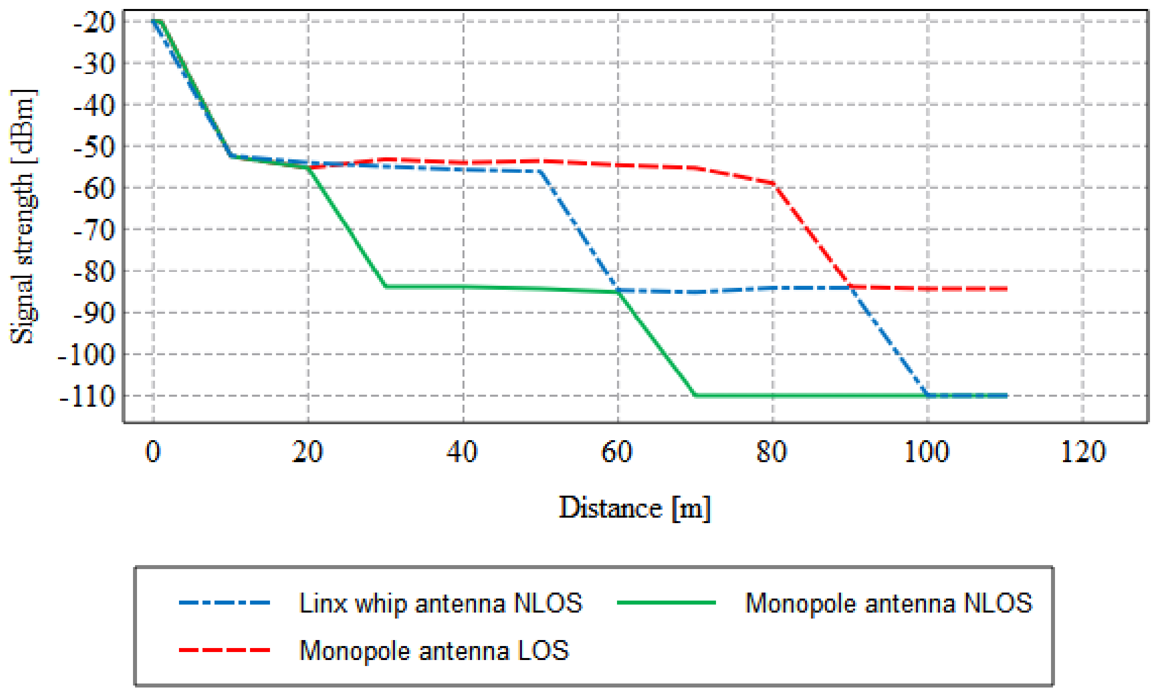

Figure 4.14. Benchmark measurement results taken in an open field

The measured received signal strength indication (RSSI) for nodes within a vineyard that are not in line of sight of each other, is shown in Figure 4.15. Both the monopole and Linx whip antenna show a signal strength going below -100 dBm at 70 m. At 60 m the monopole antenna had a 60 dBm stronger signal strength than the Linx whip antenna. Both measurements show at 70 m about 70 dBm less than the WMED results.

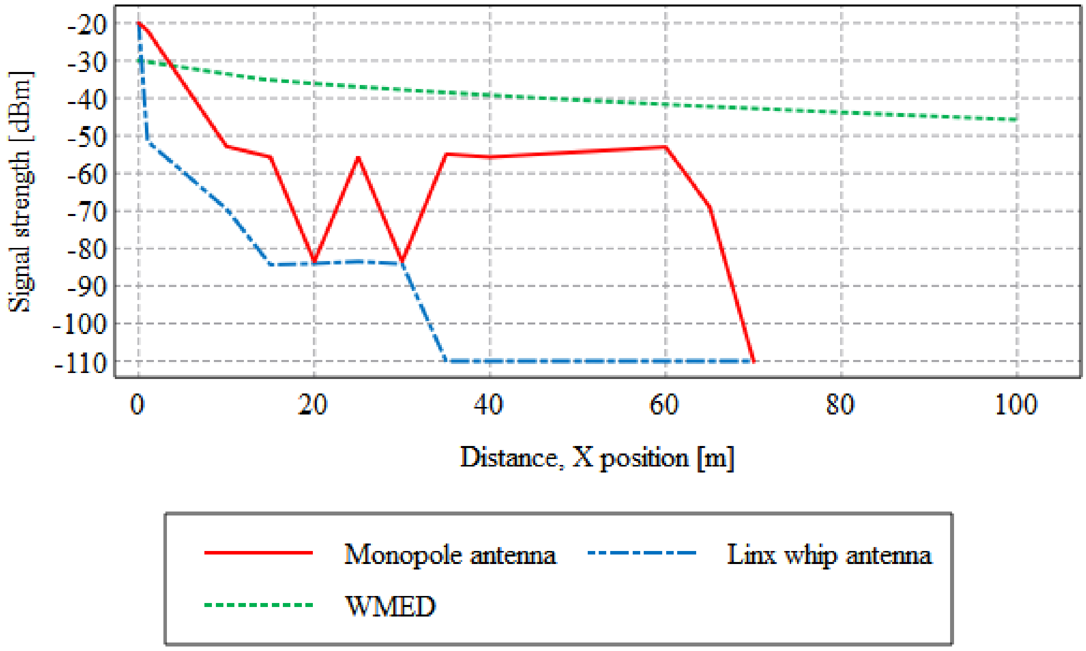

Figure 4.15. RSSI results for nodes placed on the ground in a vineyard

The results for measurements done for nodes on the ground and above the foliage when moving between the vineyard rows are shown in Figure 4.16. The same signal strength was measured at a distance of 10 rows, but at row four and row eight the node above the foliage shows a signal strength of 30 dBm more than the node on the ground.

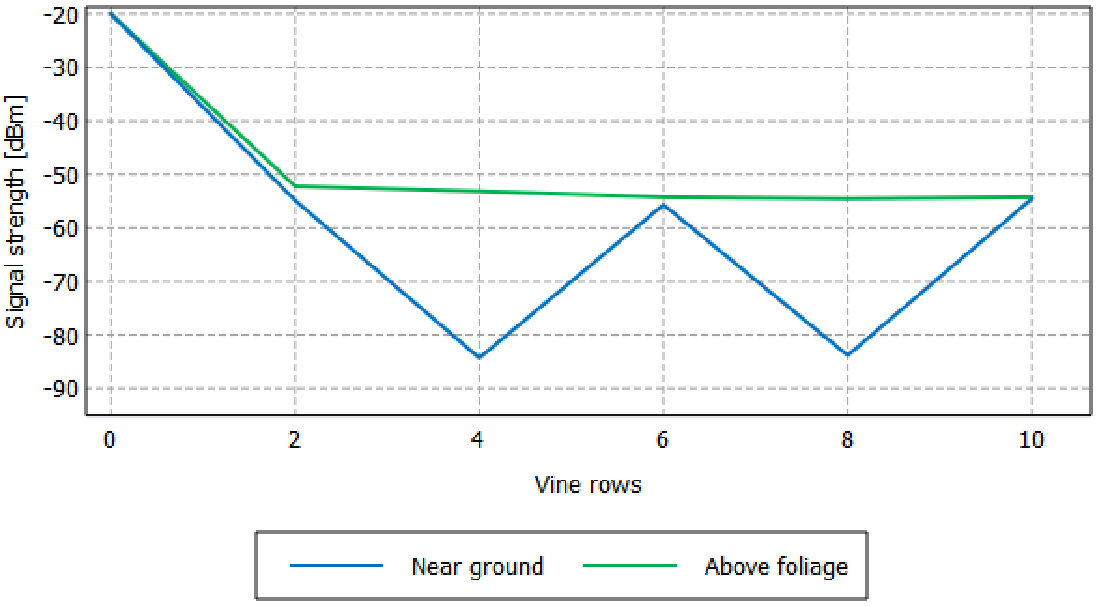

Figure 4.16. RSSI results for nodes placed on the ground versus nodes placed at the top of the canopy

Attaching a WizziMote to a quadcopter, flying at a height of 10 m, with the other node on the ground, a maximum horizontal communication distance of 90 m was achieved. The maximum height the quadcopter was flown was 60 m directly above the WizziMote on the ground with a strong signal strength of -70 dBm.

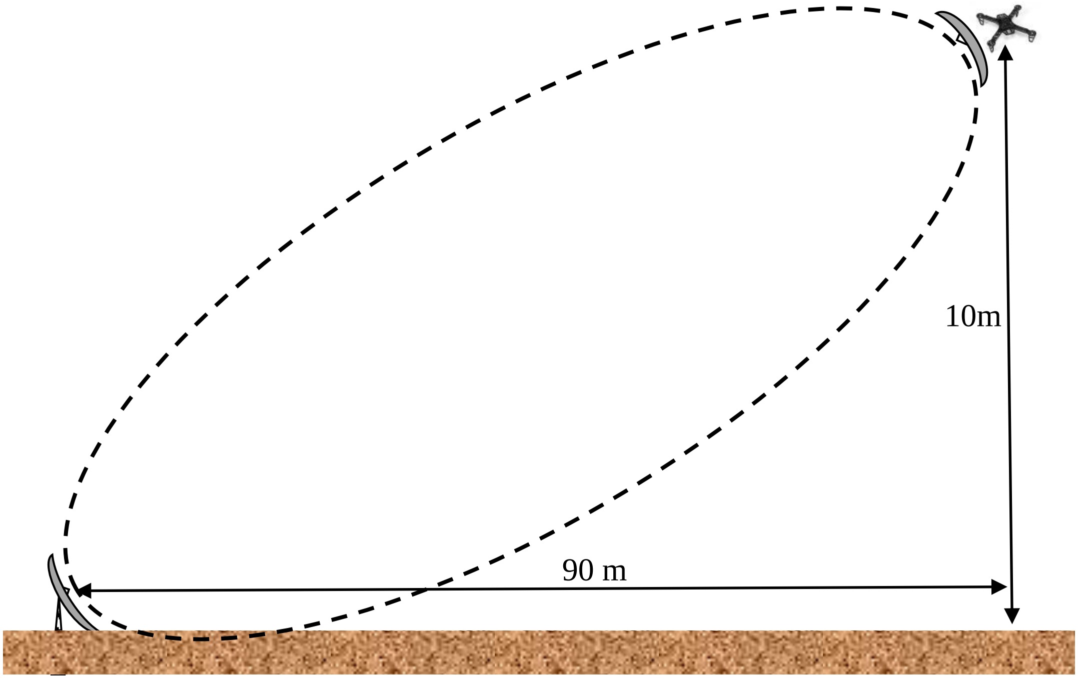

Figure 4.17. Maximum distance results from using a quadcopter

4.7.4 Simulation results

Scripts for setting up the simulations can be seen in Addendum A. To save computation time and resources the model for the vineyard has been reduced to hollow structures. Due to the repetitive nature of the vines, an array of vines was created and solved with the Domain's Green's Function Method provided by CADFEKO.

Table 4.6. Dielectric properties of the media used

Medium	**Relative permittivity**	**Dielectric loss tangent**
Foliage	1.03	0.00028
Wood	2	0.04
Soil	15	0.01

The far field radiation pattern for the monopole and Linx whip antenna is shown in Figure 4.18 and Figure 4.19 both indicating a maximum total gain of 1.5 in the horizontal direction, parallel to the ground, if the antenna is placed facing upwards. In Figure 4.20 the far field radiation pattern for the Linx whip antenna within the vineyard is shown. It shows a maximum total gain of 0.36 in a more upward direction.

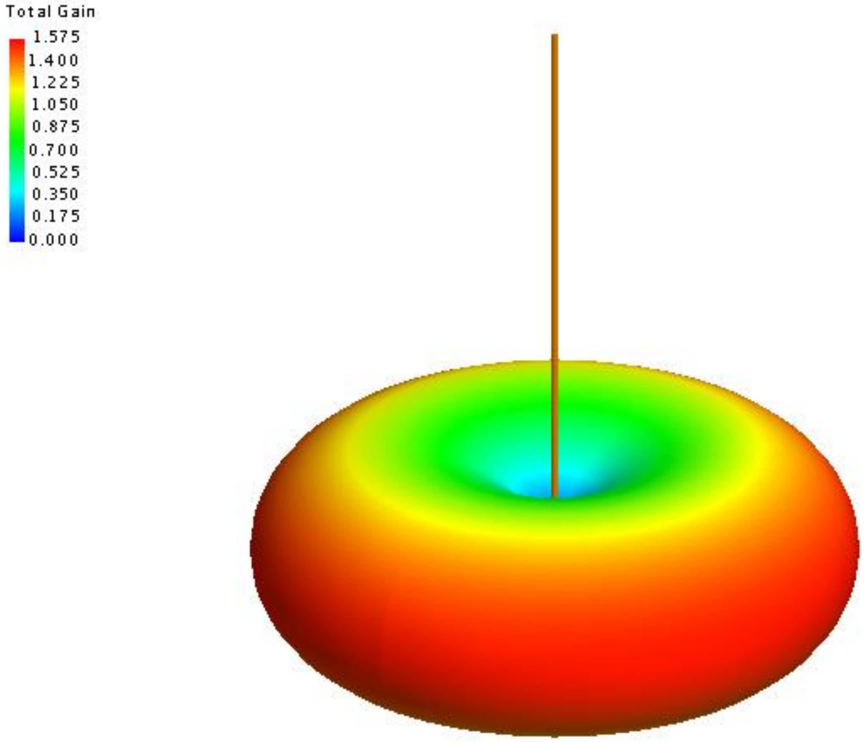

Figure 4.18. Quarter wave monopole antenna far field radiation pattern

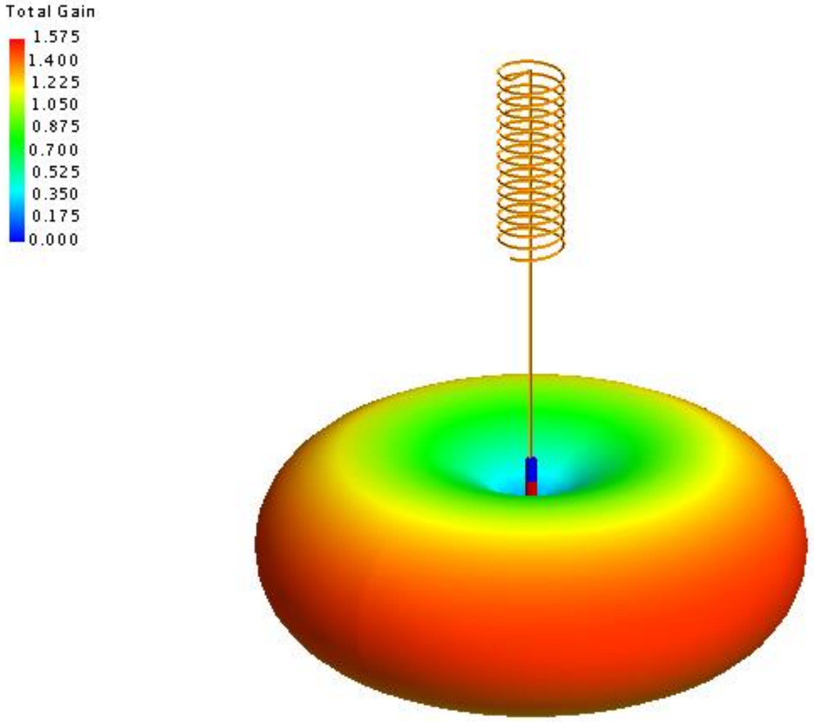

Figure 4.19. Linx whip antenna far field radiation pattern

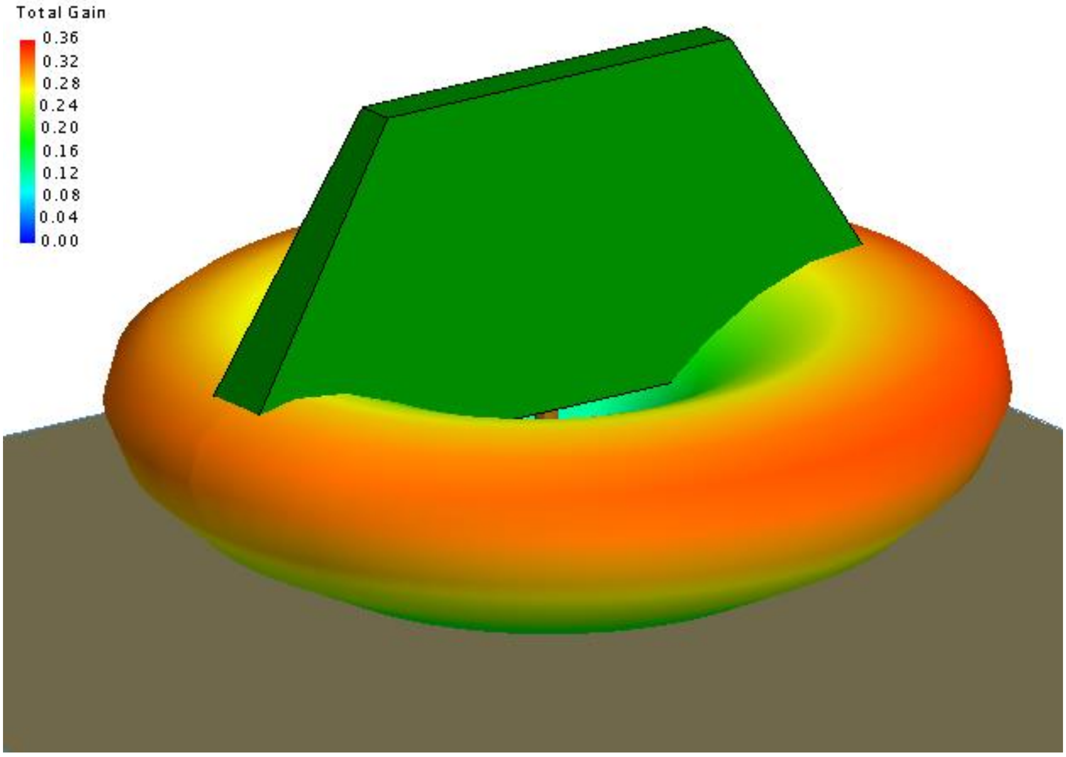

Figure 4.20. Linx whip antenna radiation pattern with vine and infinite ground plane

The efficiency of power transmission for the monopole antenna is shown in Figure 4.21 where in the presence of an infinite ground plane it is 1.64 at 433 MHz. For the Linx whip antenna in Figure 4.22 the efficiency at 433 MHz, in the presence of an infinite ground plane, is shown as 632.751.

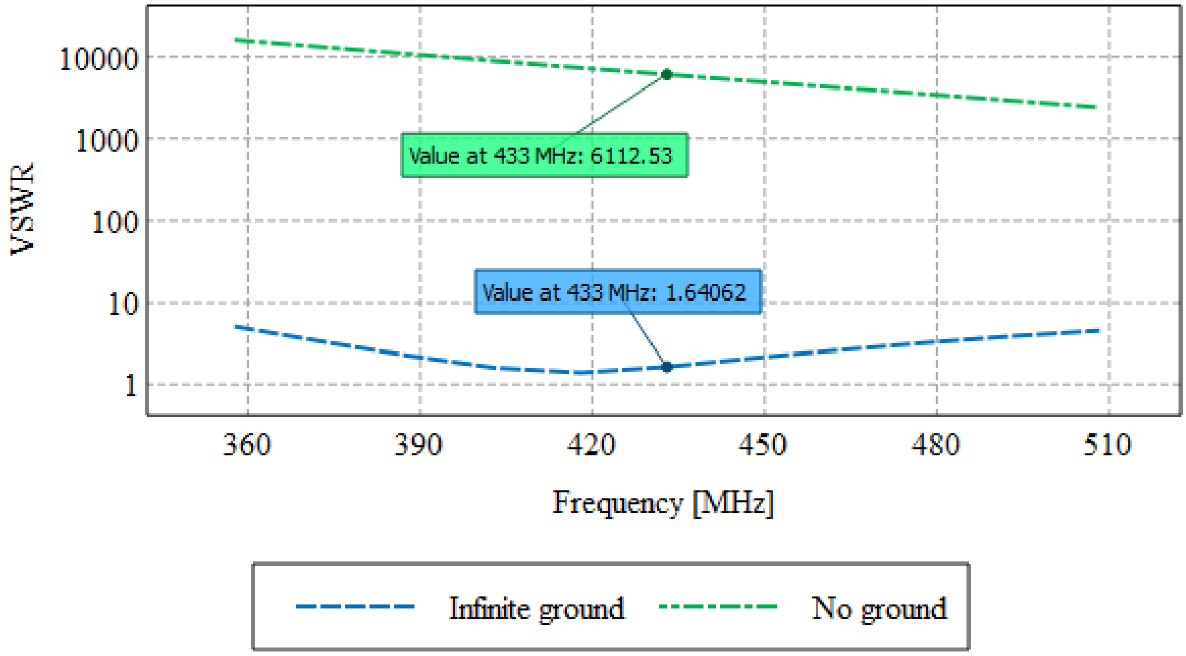

Figure 4.21. Monopole antenna VSWR results

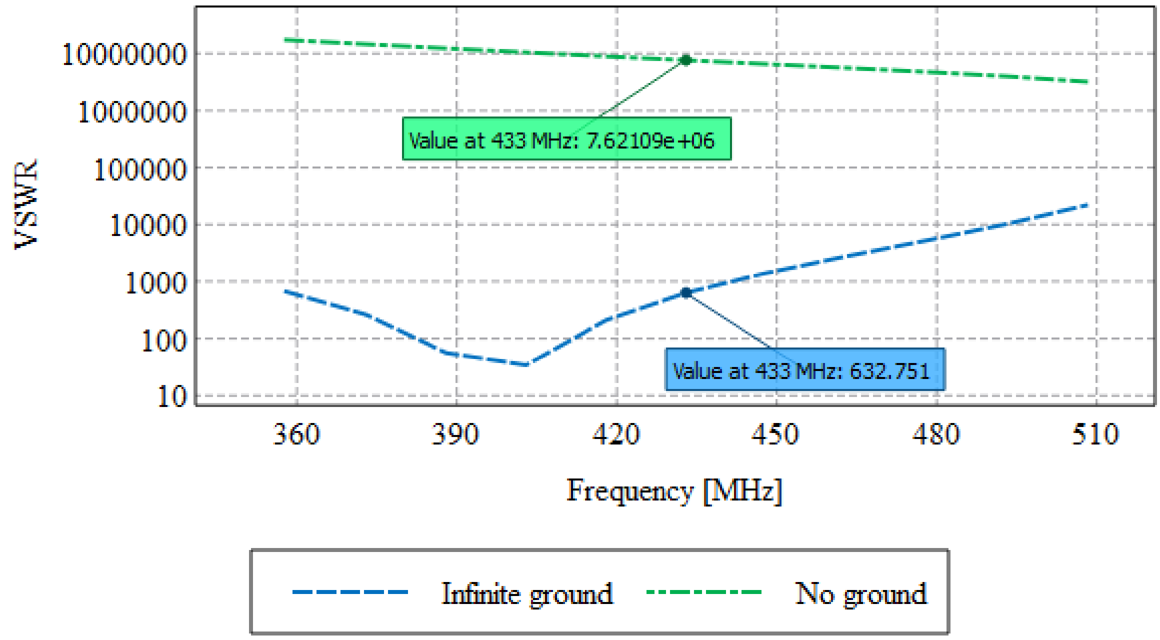

Figure 4.22. Linx whip antenna VSWR results

Figure 4.23 and Figure 4.24 illustrate the effective power and transmission range of the antennas in the vineyard. The electric near field range is set between 0 and -60 dBV/m and the effect of placing the node on the ground compared to above the foliage is illustrated.

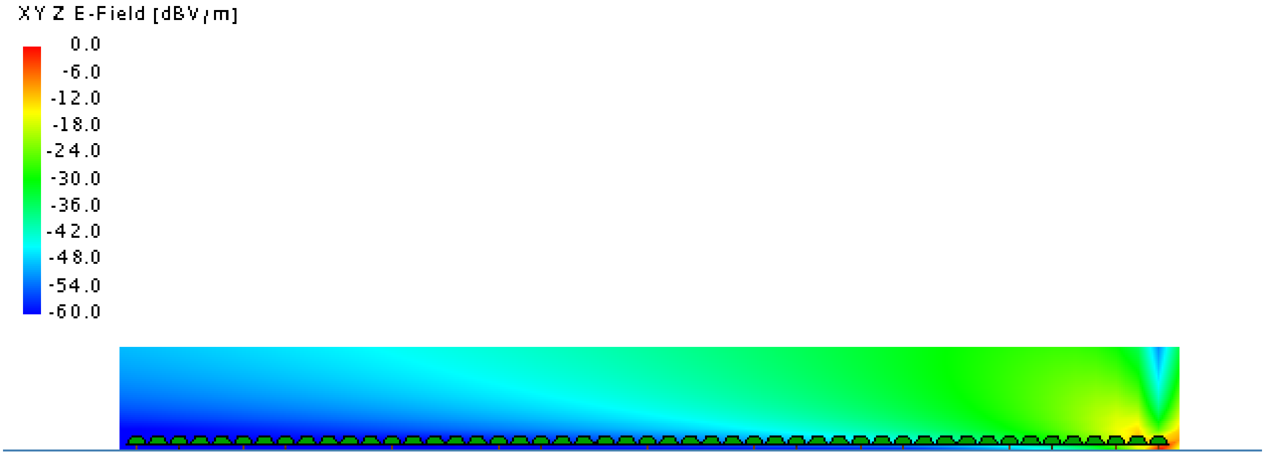

Figure 4.23. Electric near field result for antenna on the ground

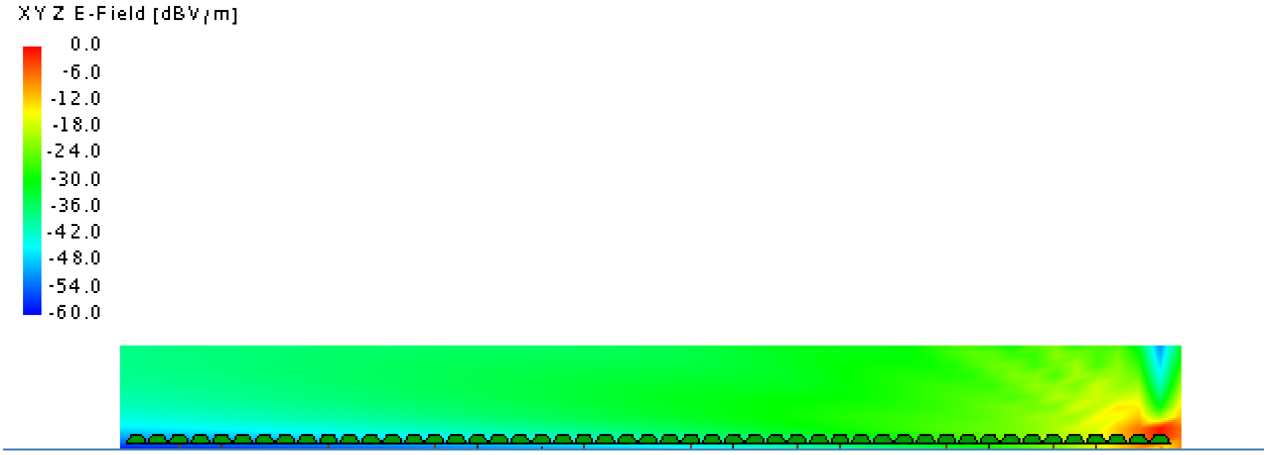

Figure 4.24. Electric near field for antenna above the foliage

In Figure 4.25 the difference in electric near field between the node on the ground and above the foliage can be seen. At 100 m the node on the ground has a loss of 30.96 dBV/m more than the node placed above the foliage.

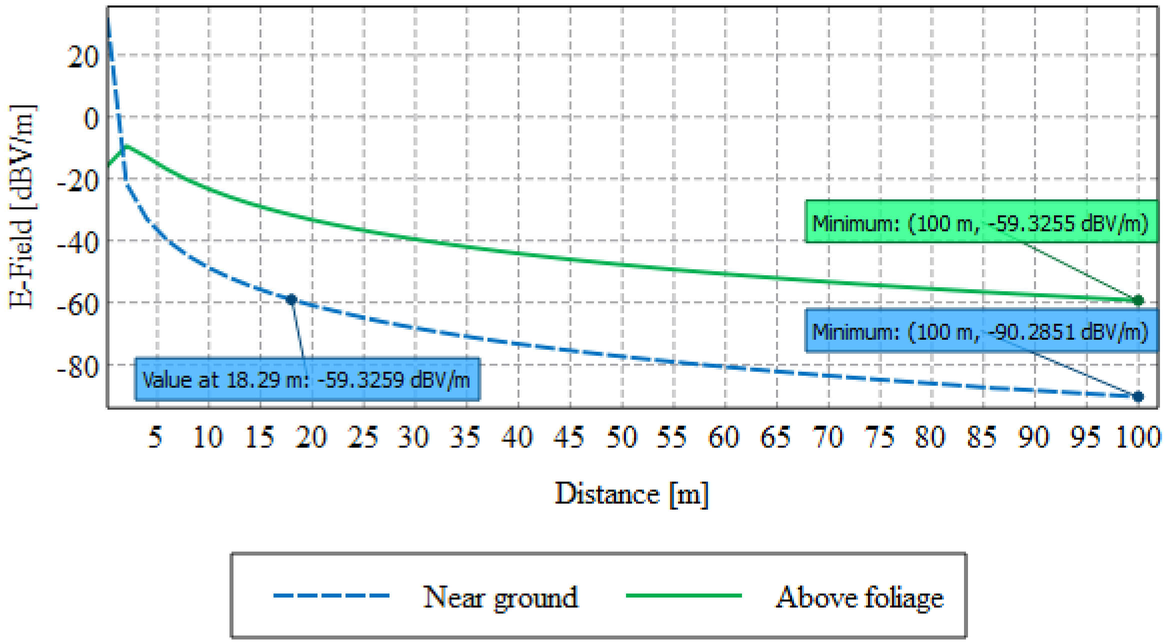

Figure 4.25. Electric near field results for antennas placed near the ground and above the foliage

The effect of increasing the transmission power of the node is illustrated in Figure 4.26. At 100 m the node transmitting at 10 mW has 20.35 dBV/m less than the node transmitting at 1 W.

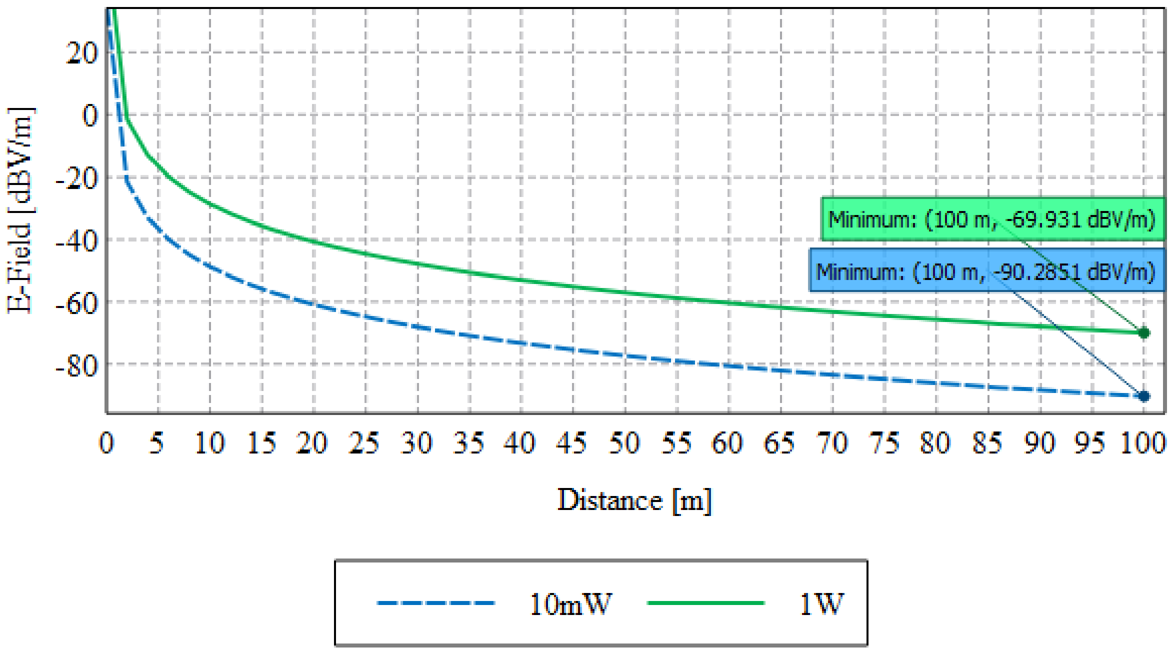

Figure 4.26. Electric near field results for antenna placed on the ground at different transmission power

A comparison between a node in an open field and one placed within the vineyard is shown in Figure 4.27. At 100 m the node within the vineyard has a loss of 5.41 dBV/m more than the node in an open field.

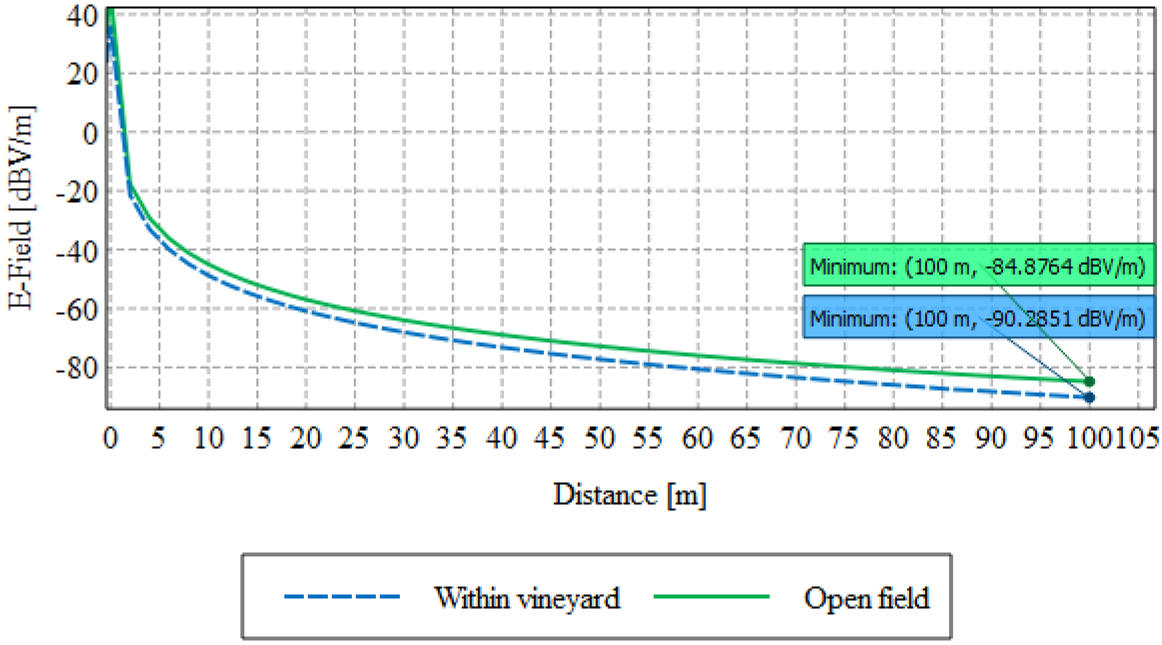

Figure 4.27. Electric near field results between antennas placed within the vineyard and one in the open field

4.8 CONCLUSION

Several options of WSN technology currently available were discussed together with results on what features are important. A solution using a quadcopter was proposed to save costs by using fewer nodes and keeping to the requirement of the FNs being deployed on the ground. The results did not work out as expected and are discussed in more detail in the next chapter. After that the final chapter reaches conclusions of the findings and proposes a possible avenue for further research in using drones together with WSNs.

CHAPTER 5 DISCUSSION

5.1 INTRODUCTION

Chapter 1 provided an introduction to the context of the problem of commercially available WSNs used in vineyards in South Africa and the possibility of optimising them. Chapter 2 discussed some literature reviewed by the researcher on WSNs and the various communication layers, protocols and standards researched as well as theory on precision agriculture and viticulture. In Chapter 3, a research methodology was described focusing on two main components. The first dealt with how the current WSN technology was assessed and the second looked at a possible avenue of optimising a WSN implementation. The results obtained from following the methodology were reported in Chapter 4. Sections 4.3 to 4.6 reported on the assessment of the current commercially available WSN technology. Results for optimising the WSN were reported in Section 4.7. This chapter will discuss the results obtained, with its structure organised in correlation with Chapter 4. The results of assessing the technology will be discussed first and then the results from the optimisations investigated. Next, some challenges identified for viticulture and commercial WSNs in South Africa will be discussed. Finally the chapter will give a short conclusion about the research that was contributed leading to the final conclusions and recommendation presented in Chapter 6.

5.2 FEASIBLE COMMERCIAL SENSORS

From the information in Section 4.4 several factors have been identified that a WSN in a vineyard should adhere to. These factors were classified and the commercial WSNs from Section 4.3 evaluated according to them. In Table 4.5 the evaluated results according to the features identified are shown. It is evident that the products available are quite sufficient in meeting most of the requirements but two nodes stand out. The ENV-Link^{TM} and CLSMP both fulfil the most important identified requirements of having local support, a communication range greater than 1 km, a robust weatherproof casing, battery lifetime of more than one year, a soil moisture sensor, a temperature sensor and finally software that manages and interprets the data gathered.

It has to be noted that the even though the Waspmote does not have local support, it stands out above all due to the following reasons:

- It provides the biggest communication range of up to 7 km, which none of the other sensors can compare with. This range is however coupled with more power consumption and installing a solar panel will be essential.
- It supports various types of radios. This allows for bigger customisation according to the farmer's requirements and scalability, for example adding an RFID reader to the nodes.
- It also provides the widest range of sensors.

Looking at what standards are being used, ZigBee with IEEE 802.15.4 is the predominant one. However, the most promising standard for agriculture, DASH7, is lacking. Taking into consideration the various radios the Waspmote already supports, it might soon include the DASH7 standard.

Section 4.5 shows the estimated costs for each commercial WSN and it is clear that the three cheapest solutions are HOBOnode, CLSMP and Waspmote. From these three the CLSMP emerges as common to both avenues (cost and features) taken in TA. CLSMP is about 25 percent cheaper than Waspmote to install, but Waspmote scales much better in increased distance between nodes where the cost per kilometre is 77 percent cheaper than CLSMP.

Taking into consideration the case study of Section 4.2 and the major advantage of CLSMP being locally manufactured, it does resolve to be the most feasible WSN to deploy in a vineyard in South Africa. The ENV-Link^{TM} is too expensive and the lack of local support for Waspmote impedes its feasibility locally.

5.3 OPTIMISED DESIGN

The second component of this dissertation investigated an optimal solution for WSNs in a South African vineyard. The methodology followed was described in Section 3.6. The requirement was that the nodes should not be visible due to theft, and should thus be closer to the ground. Theoretically, this limits the nodes that use the 2.4 GHz communication standards due to interference by foliage. The 433 MHz spectrum was a much more promising frequency and nodes (WizziMotes) using this frequency were investigated. According to the manufacturer, the communication range of the nodes is 600 m line of sight in an ideal environment with no interference.

Looking at the predicted signal strength over distance according to the WMED model seen in Figure 4.11, the signal strength at 600 m should be -45 dB, converting this to dBm 30 dB are subtracted which gives a signal strength of -75 dBm. This is well within the manufacturer's minimum receiver sensitivity of -110 dBm. It is clear that the WMED is not suitable for accurate modelling of signal propagation through a vineyard. Suitable models are still being researched and Correia, Alencar, Carvalho, Leal and Lopes (2013) used the Least Squares Method to determine coefficients of the equation for the power regression model.

The results for the calculated required Fresnel zone 1 seen in Figure 4.13 show that at 600 m, the antennas should be 10 m above the ground. Since 60 percent clearance is deemed sufficient (McLarnon, 1997), the required height above the ground is 6 m. This indicates that interference will play a major role in the requirement to place the nodes on the ground.

From the results seen in Section 4.7.3, it is clear that the desired range was not achieved. A maximum range of 110 m was achieved where the signal strength went below its lowest acceptable value of -110 dBm. The most likely reasons for this are due to scattering interference caused by not meeting the required Fresnel zone and external interference caused by other electronic equipment in the vicinity. Using directional antennas could increase the distance, but limits the node placements and wouldn't be feasible. Simulations were done to confirm the possible causes for the limited range achieved.

An approach was followed, described in Section 3.6.2.1, where the CH was elevated by attaching it to a quadcopter. The Fresnel zone height requirement of 10 m could then be met. The result obtained, shown in Figure 4.17, was discouraging. A maximum distance of 90 m was achieved. This then led the researcher to believe the specifications provided by the manufacture are unrealistic, only achievable in perfect conditions, and not applicable to real world applications.

The antenna also played a significant role in the range achieved and simulations were done to investigate this. The simulation performance of a quarter wave monopole antenna was compared to that of the Linx whip antenna used in the signal strength measurements. Figure 4.18 and Figure 4.19 show that both antennas have excellent omni-directional radiation patterns, which is ideal for the intended implementation. Placing the antenna within a vineyard, as seen in Figure 4.20, did influence the radiation pattern somewhat, reducing the effective total gain by more than 80 percent. Looking at the predicted effectiveness, the monopole antenna simulation highlights the importance of the ground plane. At 433 MHz an acceptable VSWR value should be below 2 (Silver, 1949). In Figure 4.21 this is achieved with a value of 1.64 at 433 MHz, but for the Linx whip antenna, VSWR results seen in Figure 4.22, the value simulated is far off at 632.751 at 433 MHz. This can be contributed to the lack of accurate design specifications for the antenna as well as the required matching circuit. It does highlight that the antenna might not be ideal for use with the WizziMote due to its dependency on a specific matching circuit to operate effectively.

The difference in transmission power between a node on the ground and one above the foliage is noticeable in Figure 4.23 and Figure 4.24. The blue area indicating a loss of -60 dBV/m is larger for the node placed on the ground. It is also evident from the plot shown in Figure 4.26 that communication distance is reduced by more than 80 percent. The same power is measured for the node above foliage at 100 m as for the node on the ground at 18.29 m. The effect of increasing the transmission power and how it will increase the range was shown in Figure 4.26, but applying it is not feasible since it will drain the battery power too fast as well as break regulations. It is of interest that the difference between the results for the node placed within the vineyard compared to one in an open field is much less than it ought to be. This is most likely due to simplifications for the vineyard in the simulation model due to limited resources.

5.4 CHALLENGES FOR VITICULTURE

In Section 2.4.2 several challenges related to WSNs in agriculture are mentioned. Several of these challenges are still quite evident in the results obtained from this research.

Understanding the domain still remains a challenge to most farmers. Advanced sensors providing specialised information are overwhelming. As more research and correlation is being done on these sensed data, more models will be developed that can be implemented in computer software. Software packages capable of communicating with the sensors, gathering the information and interpreting it for the farmer, will ensure faster and further growth of WSN implementations. The requirement from the software would be to inform the farmer when to irrigate, detect a coming disease and what actions to take.

Due to WSNs being used less in South Africa, contention for the radio channels are not yet being experienced. Since wine farms are much smaller size than other types of agriculture, scaling is also not perceived as a problem.

Theft is a challenge for most South African farmers which limits their options in WSNs and increases the risk of line of sight installations. The cost of replacement due to theft must be reduced, as well as removing possible incentives for stealing the nodes to sell anything that could be salvaged from it. For this reason, using solar panels is not an option and longer battery life becomes priority. This increases the requirement to hide the nodes from view. Section 4.7 showed the results of the investigation into what the effects on the communication range are when placing nodes on the ground, out of sight. Higher frequency communication protocols such as ZigBee are affected by canopy interference and require the nodes to be installed above the leaves, which makes them quite visible and a target for thieves. Lower frequency protocols such as DASH7 are less affected by the canopy growth which could make it possible to hide them, even bury the sensor nodes. It also provides the longest battery life of all current WSN standards. Unfortunately no commercial solutions exist that utilise DASH7 for WSN in agriculture.

Since the needs of the farmer are quite basic, as can be seen from

Table 4.5 where the basic sensing types are the only essential requirement, scalability and adaptability into various other domains such as harvest tracking have not yet been considered. It still remains a challenge on how such a system should integrate with any possible existing systems. This however adds to the cost of the WSN which in turn lowers the farmer's motivation to implement it.

5.5 CONCLUSION

The results of the research done on feasible commercial WSNs have been discussed. A commercially available WSN system that best meets the set requirements was identified. The results of the optimal solution devised using the DASH7 standard were discussed and concluded as promising but not feasible for commercial use. Finally, the challenges identified in the literature and encountered in this research were discussed. The final chapter summarises the main contribution of this research and concludes with suggestions for future work.

CHAPTER 6 CONCLUSION

6.1 INTRODUCTION

This chapter concludes with the main research contributed. In previous sections, the feasible commercial WSNs were discussed and categorised according to identified required features. According to the literature, the ideal WSN requires several nodes to create a network of hops for reliable connectivity, but in a commercial application this cannot be met due to high costs involved. Several commercially available sensor systems are packed with too many capabilities, which drive up costs even more. The farmer wants to install the least number of nodes required to cover the area of interest. Reducing costs of implementing and maintaining a WSN in a vineyard was the main TA factor for this dissertation.

A commercially available WSN system, continuous logging soil moisture probe (CLSMP), provided by a company called DFM, best meets the set requirements that were identified. This company has been providing WSN solutions to farmers for several years and even though the basic requirements of the farmers are being addressed, the system has room for improvement and lacks scalability in terms of the types of sensors that can be added.

An optimal solution has been devised using the DASH7 standard that focuses solely on the requirements of WSNs in vineyards in South Africa. Even though the DASH7 standard seems promising, it is still under development and not ready for commercial use. The particular requirements of placing the nodes on the ground and using fewer of them for an optimal WSN in a vineyard in South Africa could not be met. Simulations were done to determine the reason for the undesired results and it was found to be largely due to the nature of wireless communications being prone to interference from the environment and other electronic equipment.

6.2 FURTHER RESEARCH

DASH7 together with quadcopter drones presents a promising solution for WSNs in agriculture and further research in using this standard in such a manner is required. The standard must be adapted to ensure the nodes can handle interference caused by the drone. Valente *et al.* (2011) developed their own protocols for their system where a drone collected the sensor data from deployed field nodes. The BLAST concept utilised by DASH7 suits this type of data gathering (Piromalis *et al.*, 2013). Drones can fly over the field nodes within communication range and retrieve the current stored sensor readings. These nodes send bursts of data consisting of small data packets on demand. The asynchronous nature of the nodes will allow them to sleep most of the time and only send their measurements when asked by the drone, thus saving battery life. The limited bandwidth provided by DASH7 does not present any drawbacks due to the small amount of data generated by the sensors. More freedom will be provided for field node locations since line of sight between them will not be required because the drone can fly directly above it. Hiding the node will also be easier and reduces the risk of theft.

REFERENCES

Abbasi, A.Z., Islam, N. and Shaikh, Z.A. (2014). A review of wireless sensors and networks' applications in agriculture. *Computer Standards & Interfaces*, 36(2), 263-270.

Akyildiz, I.F., Su, W., Sankarasubramaniam, Y. and Cayirci, E. (2002). Wireless sensor networks: a survey. *Computer networks,* 38(4), 393-422.

Akyildiz, I.F.andVuran, M.C. (2010). *Wireless sensor networks,* Wiley.

Al-Karaki, J.N. & Kamal, A.E. (2004). Routing techniques in wireless sensor networks: a survey. *Wireless Communications, IEEE,* 11(6), 6-28.

Al-Karaki, J.N. & Al-Mashaqbeh, G.A. (2007). Energy-centric routing in wireless sensor networks. *Microprocessors and Microsystems*, 31(4), 252-262.

Alsaify, B.A. & Thompson, D.R. (2010). Pendulum: An energy efficient protocol for Wireless Sensor Networks, In: *Sensors Applications Symposium (SAS), 2010 IEEE,* 273.

Anurag, D., Roy, S., Bandyopadhyay, S. & Kolkata, I. (2008). Agro-sense: precision agriculture using sensor-based wireless mesh networks, In: *Innovations in NGN: Future Network and Services, 2008. K-INGN 2008. First ITU-T Kaleidoscope Academic Conference,* 383.

Baker, N. (2005). ZigBee and Bluetooth strengths and weaknesses for industrial applications. *Computing & Control Engineering Journal*, 16(2), 20-25.

Baronti, P., Pillai, P., Chook, V.W.C., Chessa, S., Gotta, A. and Hu, Y.F. (2007). Wireless sensor networks: A survey on the state of the art and the 802.15. 4 and ZigBee standards. *Computer Communications,* 30(7), 1655-1695.

Beckwith, R., Teibel, D. & Bowen, P. (2004). Unwired wine: Sensor networks in vineyards, In: *Sensors, 2004. Proceedings of IEEE,* Ieee: 561.

Biradar, R.V., Patil, V., Sawant, S. and Mudholkar, R. (2009). Classification and comparison of routing protocols in wireless sensor networks. *Special Issue on Ubiquitous Computing Security Systems, UbiCC Journal,* 4704-711.

Blackmore, S. (1994). Precdision farming: an introduction. *Outlook on Agriculture,* 23(4), 275-280.

Boukerche, A., Cheng, X. & Linus, J. (2003). Energy-aware data-centric routing in microsensor networks, In: *Proceedings of the 6th ACM international workshop on Modeling analysis and simulation of wireless and mobile systems,* ACM: 42.

Braginsky, D. & Estrin, D. (2002). Rumor routing algorthim for sensor networks, In: *Proceedings of the 1st ACM international workshop on Wireless sensor networks and applications,* ACM: 22.

Buratti, C., Conti, A., Dardari, D. and Verdone, R. (2009). An Overview on Wireless Sensor Networks Technology and Evolution. *Sensors,* 9(9), 6869-6896.

Burrell, J., Brooke, T. and Beckwith, R. (2004). Vineyard computing: Sensor networks in agricultural production. *Pervasive Computing, IEEE,* 3(1), 38-45.

Camalie Networks LLC. (2009). Wireless Agricultural Monitoring and Control. http://99.115.132.118/html. Last accessed 26 August 2015.

Camilli, A., Cugnasca, C.E., Saraiva, A.M., Hirakawa, A.R. and Corrêa, P.L.P. (2007). From wireless sensors to field mapping: Anatomy of an application for precision agriculture. *Computers and Electronics in Agriculture,* 58(1), 25-36.

Chen, B., Jamieson, K., Balakrishnan, H. & Morris, R. (2001). Span: An energy-efficient coordination algorithm for topology maintenance in ad hoc wireless networks, In: *Proceedings of the 7th annual international conference on Mobile computing and networking,* ACM: 85.

Chu, M., Haussecker, H. and Zhao, F. (2002). Scalable information-driven sensor querying and routing for ad hoc heterogeneous sensor networks. *International Journal of High Performance Computing Applications,* 16(3), 293-313.

Chukhlantsev, A.A., Shutko, A.M. and Golovachev, S.P. (2003). Attenuation of electromagnetic waves by vegetation canopies in the 100-1000 MHz frequency band. *Journal of Radio Electronics,* (2).

Correia, F.P., Alencar, M.S., Carvalho, F., Leal, B.G. & Lopes, W.T. (2013). Propagation analysis in Precision Agriculture environment using XBee devices, In: *Microwave & Optoelectronics Conference (IMOC), 2013 SBMO/IEEE MTT-S International,* IEEE: 1.

Dargie, W.andPoellabauer, C. (2010). *Fundamentals of wireless sensor networks: theory and practice,* John Wiley & Sons Inc.

Deljoo, A. & Keshtgari, M. (2012). A Wireless Sensor Network Solution for Precision Agriculture Based on Zigbee Technology. *Advances in Molecular Imaging,* 4.

DFM Software Solutions. (2015). Homepage of DFM Software Solutions. http://www.dfmsoftware.co.za. Last accessed 26 August 2015.

Goyal, D. & Tripathy, M.R. (2012) Routing Protocols in Wireless Sensor Networks: A Survey, In: *Advanced Computing & Communication Technologies (ACCT), 2012 Second International Conference on,* 474.

Hall, A., Lamb, D., Holzapfel, B. and Louis, J. (2002). Optical remote sensing applications in viticulture-a review. *Australian Journal of Grape and Wine Research*, 8(1), 36-47.

He, T., Stankovic, J.A., Lu, C. & Abdelzaher, T. (2003). SPEED: A stateless protocol for real-time communication in sensor networks, In: *Distributed Computing Systems, 2003. Proceedings. 23rd International Conference on,* IEEE: 46.

Heinzelman, W.R., Chandrakasan, A. & Balakrishnan, H. (2000). Energy-efficient communication protocol for wireless microsensor networks, In: *System Sciences, 2000. Proceedings of the 33rd Annual Hawaii International Conference on,* IEEE: 10 pp. vol. 2.

Heinzelman, W.R., Kulik, J. & Balakrishnan, H. (1999). Adaptive protocols for information dissemination in wireless sensor networks, In: *Proceedings of the 5th annual ACM/IEEE international conference on Mobile computing and networking,* ACM: 174.

Holler, M. (2010). Homepage of Camalie Vineyards. http://camalie.com. Last accessed 26 August 2015.

Howitt, I. & Gutierrez, J.A. (2003). IEEE 802.15. 4 low rate-wireless personal area network coexistence issues, In: *Wireless Communications and Networking, 2003. WCNC 2003. 2003 IEEE,* IEEE: 1481.

IEEE 802 Working Group (2003). Standard for Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low Rate Wireless Personal Area Networks (LR-WPANs). *ANSI/IEEE 802.15,* 4.

Intanagonwiwat, C., Govindan, R. & Estrin, D. (2000). Directed diffusion: a scalable and robust communication paradigm for sensor networks, In: *Proceedings of the 6th annual international conference on Mobile computing and networking,* ACM: 56.

Jedermann, R., Behrens, C., Westphal, D. and Lang, W. (2006). Applying autonomous sensor systems in logistics—Combining sensor networks, RFIDs and software agents. *Sensors and Actuators A: Physical,* 132(1), 370-375.

Jia Zhao, Chunming Qiao, Seokhoon Yoon & Sudhaakar, R.S. (2011). Enabling Multi-Hop Communications through Cross-Layer Design for Hybrid WSNs with Transmit-Only Nodes, In: *Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE,* 1.

Karapistoli, E., Pavlidou, F.N., Gragopoulos, I. and Tsetsinas, I. (2010). An overview of the IEEE 802.15. 4a standard. *Communications Magazine, IEEE,* 48(1), 47-53.

Karl, H.andWillig, A. (2007). *Protocols and architectures for wireless sensor networks,* Wiley-Interscience.

Khader, O. & Willig, A. (2013). An energy consumption analysis of the Wireless HART TDMA protocol. *Computer Communications,* 36(7), 804-816.

Kiepert, J. & Sin Ming Loo (2012). A unified wireless sensor network framework, In: *Systems Conference (SysCon), 2012 IEEE International*, 1.

Konstantinos, K., Apostolos, X., Panagiotis, K. & George, S. (2007). Topology Optimization in Wireless Sensor Networks for Precision Agriculture Applications, In: *Sensor Technologies and Applications, 2007. SensorComm 2007. International Conference on*, 526.

Kuhn, F., Wattenhofer, R. & Zollinger, A. (2003). Worst-case optimal and average-case efficient geometric ad-hoc routing, In: *Proceedings of the 4th ACM international symposium on Mobile ad hoc networking & computing*, ACM: 267.

Lansford, J., Stephens, A. and Nevo, R. (2001). Wi-Fi (802.11 b) and Bluetooth: enabling coexistence. *Network, IEEE,* 15(5), 20-27.

Lei Xiao & Lejiang Guo (2010). The realization of precision agriculture monitoring system based on wireless sensor network, In: *Computer and Communication Technologies in Agriculture Engineering (CCTAE), 2010 International Conference On*, 89.

Lennvall, T., Svensson, S. & Hekland, F. (2008). A comparison of WirelessHART and ZigBee for industrial applications, In: *Factory Communication Systems, 2008. WFCS 2008. IEEE International Workshop on*, IEEE: 85.

Lewis, F.L. (2004). Wireless Sensor Networks, *Smart Environments* John Wiley & Sons, Inc.

Li, L. & Halpern, J.Y. (2001). Minimum-energy mobile wireless networks revisited, In: *Communications, 2001. ICC 2001. IEEE International Conference on,* IEEE: 278.

Li, Q., Aslam, J. & Rus, D. (2001). Hierarchical power-aware routing in sensor networks, In: *Proceedings of the DIMACS workshop on pervasive networking*.

Libelium. (2015). Homepage of Libelium. http://www.libelium.com. Last accessed 26 August 2015.

Lindsey, S. & Raghavendra, C.S. (2002). PEGASIS: Power-efficient gathering in sensor information systems, In: *Aerospace conference proceedings, 2002. IEEE,* IEEE: 3.

Lindsey, S., Raghavendra, C.S. & Sivalingam, K. (2001). Data gathering in sensor networks using the energy* delay metric, In: *Proceedings of the IPDPS Workshop on Issues in Wireless Networks and Mobile Computing,* Citeseer: 23.

Lindsey, S., Raghavendra, C. and Sivalingam, K.M. (2002). Data gathering algorithms in sensor networks using energy metrics. *Parallel and Distributed Systems, IEEE Transactions on*, 13(9), 924-935.

Linear Technology Corporation. (2015). Homepage of Linear Technology Corporation. http://linear.com. Last accessed 26 August 2015.

Liu, L. (2011). A Wireless sensor network architecture for diversiform deployment environments. *Journal of Networks*, 6(3), 482-489.

Lonbale, N.V., Gupta, S. & Bhute, R.S. (2012). Energy Conservation of WSN using Routing Protocol, In: *IJCA Proceedings on National Conference on Innovative Paradigms in Engineering and Technology (NCIPET 2012),* Foundation of Computer Science (FCS): 5.

LORD Corporation. (2015). Homepage of LORD Corporation. http://www.microstrain.com/wireless. Last accessed 26 August 2015.

Manjeshwar, A. & Agrawal, D.P. (2002). APTEEN: A hybrid protocol for efficient routing and comprehensive information retrieval in wireless sensor networks, In: *Proceedings of the 16th International Parallel and Distributed Processing Symposium,* 48.

Mareca Hatler,D.G. (2008). WSN for Smart Crops. http://onworld.com/research/smartcrops/vip. Last accessed 26 August 2015.

McLarnon, B. (1997). VHF/UHF/microwave radio propagation: A primer for digital experimenters, In: *TAPR/ARRL Digital Communications Conference*.

MEMSIC Powerful Sensing Solutions. (2015). Homepage of MEMSIC. http://www.memsic.com. Last accessed 26 August 2015.

Microstrain® Sensing Systems. (2015). Wireless Sensor Networks LXRS® Data Communications Protocol. http://files.microstrain.com/Wireless-Sensor-Networks-LXRS-Data-Communication-Protocol.pdf. Last accessed 26 August 2015.

Millennial Net. (2015). Homepage of Millennial Net. http://millennialnet.net. Last accessed 26 August 2015.

Morais, R., Fernandes, M.A., Matos, S.G., Serôdio, C., Ferreira, P. and Reis, M. (2008). A ZigBee multi-powered wireless acquisition device for remote sensing applications in precision viticulture. *Computers and Electronics in Agriculture*, 62(2), 94-106.

Morshed, M.S.J. & Hossain, M.S. (2009). An Efficient Implementation Approach for Wireless Sensor Network, In: *Computer Science and its Applications, 2009. CSA '09. 2nd International Conference on,* 1.

National Instruments. (2015). Homepage of National Instruments. http://southafrica.ni.com. Last accessed 26 August 2015.

Niculescu, D. & Nath, B. (2003). Trajectory based forwarding and its applications, In: *Proceedings of the 9th annual international conference on Mobile computing and networking,* ACM: 260.

Norair, J. (2009). Introduction to DASH7 technologies. *Dash7 Alliance Low Power RF Technical Overview,* Whitepaper, 1-22.

Obalum, S.E., Ezenne, G.I., Watanabe, Y. and Wakatsuki, T. (2011). Contemporary Global Issue of Rising Water Scarcity for Agriculture: The Quest for Effective and Feasible Soil Moisture and Free-Water Surface Conservation Strategies. *Journal of Water Resource and Protection,* 3166-175.

Onset HOBO® Data Loggers. (2015). Homepage of Onset. http://www.onsetcomp.com. Last accessed 26 August 2015.

Orndorff, A.M. (2004). *Transceiver design for ultra-wideband communications,* Doctoral dissertation, Virginia Polytechnic Institute and State University.

Panchard, J. (2008). *Wireless sensor networks for marginal farming in India,* Doctoral dissertation, Ecole Polytechnique Fédérale de Lausanne.

Peres, E., Fernandes, M.A., Morais, R., Cunha, C.R., LÃ³pez, J.A., Matos, S.R., Ferreira, P.J.S.G. and Reis, M.J.C.S. (2011). An autonomous intelligent gateway infrastructure for in-field processing in precision viticulture. *Computers and Electronics in Agriculture,* 78(2), 176.

Piromalis, D., Arvanitis, K. & Sigrimis, N. (2013). DASH7 Mode 2: A Promising Perspective for Wireless Agriculture, In: *Agricontrol,* 127.

Pister, K. & Doherty, L. (2008). TSMP: Time synchronized mesh protocol. *IASTED Distributed Sensor Networks,* 391-398.

Radmand, P., Talevski, A., Petersen, S. & Carlsen, S. (2010). Comparison of industrial WSN standards, In: *Digital Ecosystems and Technologies (DEST), 2010 4th IEEE International Conference on,* IEEE: 632.

Raman, B. & Chebrolu, K. (2008). Censor networks: a critique of sensor networks from a systems perspective. *ACM SIGCOMM Computer Communication Review,* 38(3), 75-78.

Rashvand, H.F., Yi, W.D. and Cui, L. (2011). Wireless Sensor Networks (WSN) 2011. *Wireless Sensor Systems, IET,* 1(4), 179-180.

Rinaldo,R. and Klaasse,A. (2011). Grapelook - A service to improve water use efficiency of vineyards in South Africa. https://artes-apps.esa.int/projects/grapelook. Last accessed 26 August 2015.

Rodoplu, V. & Meng, T.H. (1999). Minimum energy mobile wireless networks. *Selected Areas in Communications, IEEE Journal on,* 17(8), 1333-1344.

Ruiz García, L., Barreiro Elorza, P., Rodríguez-Bermejo, J. and Robla, J. (2007). Review: Monitoring the intermodal, refrigerated transport of fruit using sensor networks. *Spanish Journal of Agricultural Research,* (2), 142-156.

Ruiz-Garcia, L., Barreiro, P. and Robla, J. (2008). Performance of ZigBee-based wireless sensor nodes for real-time monitoring of fruit logistics. *Journal of Food Engineering,* 87(3), 405-415.

Ruiz-Garcia, L., Lunadei, L., Barreiro, P. and Robla, I. (2009). A review of wireless sensor technologies and applications in agriculture and food industry: state of the art and current trends. *Sensors*, 9(6), 4728-4750.

Sadagopan, N., Krishnamachari, B. & Helmy, A. (2003). The ACQUIRE mechanism for efficient querying in sensor networks, In: *Sensor Network Protocols and Applications, 2003. Proceedings of the First IEEE. 2003 IEEE International Workshop on,* IEEE: 149.

Shan, Q., Liu, Y., Prosser, G. & Brown, D. (2004). Wireless intelligent sensor networks for refrigerated vehicle, In: *Emerging Technologies: Frontiers of Mobile and Wireless Communication, 2004. Proceedings of the IEEE 6th Circuits and Systems Symposium on*, IEEE: 525.

Shi, Q. (2007). Power management in networked sensor radios a network energy model, In: *Sensors Applications Symposium, 2007. SAS'07. IEEE,* IEEE: 1.

Silicon Labs. (2015). Homepage of Silicon Labs. http://www.silabs.com/Pages/default.aspx. Last accessed on 26 August 2015.

Singh, S.K., Singh, M. and Singh, D. (2010). Routing Protocols in Wireless Sensor Networks–A Survey. *International Journal of Computer science and engineering Survey (IJCSES),* 1(2), 63-83.

Singh, I. & Bansal, M. (2011). Monitoring Water Level in Agriculture Using Sensor Networks. *International Journal of Soft Computing and Engineering,* 1(5), 2231-2307.

Song, J., Han, S., Mok, A.K., Chen, D., Lucas, M. & Nixon, M. (2008). WirelessHART: Applying wireless technology in real-time industrial process control, In: *Real-Time and Embedded Technology and Applications Symposium, 2008. RTAS'08. IEEE,* IEEE: 377.

Stojmenovic, I. & Lin, X. (1999). GEDIR: Loop-free location based routing in wireless networks, In: *Proc. IASTED Int. Conf. on Parallel and Distributed Computing and Systems*, 1025.

Tennina, S., Bouroche, M., Braga, P., Gomes, R., Alves, M., Mirza, F., Ciriello, V., Carrozza, G., Santos, M. & Garg, A. (2011). EMMON: A System Architecture for Large-Scale, Dense and Real-Time WSNs, In: *Poster Session of the 8th European Conference on Wireless Sensor Networks (EWSN 2011), Bonn, Germany*, 59.

Tran, T.A. & Daim, T. (2008). A taxonomic review of methods and tools applied in technology assessment. *Technological Forecasting and Social Change*, 75(9), 1396-1405.

Valente, J., Sanz, D., Barrientos, A., Cerro, J.d., Ribeiro, Á and Rossi, C. (2011). An air-ground wireless sensor network for crop monitoring. *Sensors*, 11(6), 6088-6108.

Vine Tech Equipment. (2015). Homepage of Vine Tech Equipment. http://vinetechequipment.com/Spectron.htm. Last accessed 26 August 2015.

Von Hippel, A.R. (1954). *Dielectric materials and applications*, Artech House on Demand.

Wang, N., Zhang, N. and Wang, M. (2006). Wireless sensors in agriculture and food industry—Recent development and future perspective. *Computers and Electronics in Agriculture*, 50(1), 1-14.

Wang, Y., Wang, Y., Qi, X., Xu, L., Chen, J. and Wang, G. (2010). L3SN: A Level-Based, Large-Scale, Longevous Sensor Network System for Agriculture Information Monitoring. *Wireless Sensor Network*, 2(9), 655-660.

Wark, T., Corke, P., Sikka, P., Klingbeil, L., Guo, Y., Crossman, C., Valencia, P., Swain, D. and Bishop-Hurley, G. (2007). Transforming agriculture through pervasive wireless sensor networks. *Pervasive Computing, IEEE*, 6(2), 50-57.

Weissberger, M.A. (1982). An initial critical summary of models for predicting the attenuation of radio waves by trees, *Technical Report*, DTIC Document.

Wireless Sensors. (2015). Homepage of Wireless Sensors. http://www.wirelesssensors.com. Last accessed 26 August 2015.

Michaël, A. (2015). Homepage of WizziLab S.A.S. http://www.wizzilab.com. Last accessed 26 August 2015.

Xing, G., Lu, C., Pless, R. & Huang, Q. (2004). On greedy geographic routing algorithms in sensing-covered networks, In: *International Symposium on Mobile Ad Hoc Networking & Computing: Proceedings of the 5 th ACM international symposium on Mobile ad hoc networking and computing*, 31.

Xu, Y., Heidemann, J. & Estrin, D. (2001). Geography-informed energy conservation for ad hoc routing, In: *Proceedings of the 7th annual international conference on Mobile computing and networking,* ACM: 70.

Yao, Y. & Gehrke, J. (2002). The cougar approach to in-network query processing in sensor networks. *ACM Sigmod Record,* 31(3), 9-18.

Ye, F., Luo, H., Cheng, J., Lu, S. & Zhang, L. (2002). A two-tier data dissemination model for large-scale wireless sensor networks, In: *Proceedings of the 8th annual international conference on Mobile computing and networking,* ACM: 148.

Younis, O. & Fahmy, S. (2004). HEED: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks. *Mobile Computing, IEEE Transactions on*, 3(4), 366-379.

Yu, X., Wu, P., Han, W. and Zhang, Z. (2012). The research of an advanced wireless sensor networks for agriculture. *African Journal of Agricultural Research,* 7(5), 851-858.

Yu, Y., Govindan, R. and Estrin, D. (2001) Geographical and energy aware routing: A recursive data dissemination protocol for wireless sensor networks, *Technical Report ucla/csd-tr-01-0023,* UCLA Computer Science Department.

Zhang Ruirui, Chen Liping, Guo Jianhua, Meng Zhijun & Xu Gang (2010). An energy-efficient wireless sensor network used for farmland soil moisture monitoring, In: *Wireless Sensor Network, 2010. IET-WSN. IET International Conference on*, 2.

Zhang, W., He, Y., Liu, F., Miao, C., Sun, S., Liu, C. and Jin, J. (2012). Research on WSN channel fading model and experimental analysis in orchard environment, *Computer and Computing Technologies in Agriculture V* Springer.

Zheng, J. (2009). Network Architectures and Protocol Stack. *Wireless Sensor Networks*, 19-33.

Zheng, J. and Jamalipour, A. (2009) *Wireless sensor networks: a networking perspective,* John Wiley & Sons.

Zhou, J., Cao, Q., Li, C. and Huang, R. (2010). A genetic algorithm based on extended sequence and topology encoding for the multicast protocol in two-tiered WSN. *Expert Systems with Applications*, 37(2), 1684-1695.

Zorzi, M. & Rao, R.R. (2003). Geographic random forwarding (GeRaF) for ad hoc and sensor networks: multihop performance. *Mobile Computing, IEEE Transactions on,* 2(4), 337-348.

ADDENDUM A

The following Lua scripts can be run in CADFEKO 14.0 to reproduce the simulations.

- monopole.lua

```
-- Construct a quarter-wave_monopole antenna
function constructAntenna()
    -- Create Variables
    freq = project.Variables:Add("freq", "433e6")
    lambda = project.Variables:Add("lambda", "c0/freq")
    top = project.Variables:Add("top", "lambda/4")

    -- Create antenna geometry
    a = project.NamedPoints:Add("a", 0, 0, 0)
    b = project.NamedPoints:Add("b", 0, 0, top)
    line = project.Geometry:AddLine(a, b)
    line.Label = "Antenna"

    -- Create Port
    port = project.Ports:AddWirePort(line.Wires[1])

    -- Add a Voltage source to the port
    config.Sources:AddVoltageSource(port)
end

function setupAntennaSolutionConfiguration()
    -- Set total source power
    properties = config.Power:GetProperties()
    properties.ScaleSettings =
cf.Enums.PowerScaleSettingsEnum.TotalSourcePower
    properties.SourcePower = "10e-3"
    config.Power:SetProperties(properties)

    -- Request a 3D pattern far field result
    config.FarFields:Add3DPattern()
end
```

- quarterwave_antenna_performance.lua

```
-- Setup and run simulations for quarter-wave monopole antenna
require "monopole"

app = cf.GetApplication()
project = app:NewProject()
config = project.SolutionConfigurations[1]

constructAntenna()
setupAntennaSolutionConfiguration()

-- Set the frequency range to discrete linearly spaced frequency
samples
properties = config.Frequency:GetProperties()
properties.End = "freq+75e6"
properties.NumberOfDiscreteValues = "11"
properties.RangeType =
cf.Enums.FrequencyRangeTypeEnum.LinearSpacedDiscrete
properties.Start = "freq-75e6"
config.Frequency:SetProperties(properties)

-- Define an infinite metallic ground plane
project.GroundPlane.DefinitionMethod =
cf.Enums.GroundPlaneDefinitionMethodEnum.PEC

-- Mesh the model and run the solver
project.Mesher.Settings.WireRadius = "1e-3"
project.Mesher:Mesh()

-- Save the model and run the FEKO solver
app:SaveAs("quarterwave_monopole.cfx")
project.Launcher:RunFEKO()

project.GroundPlane.DefinitionMethod =
cf.Enums.GroundPlaneDefinitionMethodEnum.Homogeneous
project.Mesher:Mesh()
app:SaveAs("quarterwave_monopole_without_ground.cfx")
project.Launcher:RunFEKO()
```

- linx_antenna.lua

```
-- Construct the Linx whip antenna
function constructAntenna()
    --Create Variables
    freq = project.Variables:Add("freq", "433e6")
    height = project.Variables:Add("height", "15")
    lambda = project.Variables:Add("lambda", "c0/freq")
    radius = project.Variables:Add("radius", "2.5")
    top = project.Variables:Add("top", "40")
    turns = project.Variables:Add("turns", "15")

    -- Create antenna geometry
    properties = cf.Polyline.GetDefaultProperties()
    properties.Corners[1].N = "top"
    properties.Corners[1].U = "2.5"
    properties.Corners[1].V = "0"
    properties.Corners[2].N = "top"
    properties.Corners[2].U = "0"
    properties.Corners[2].V = "0"
    properties.Corners[3] = {}
    properties.Corners[3].N = "0"
    properties.Corners[3].U = "0"
    properties.Corners[3].V = "0"
    properties.Label = "Polyline1"
    line = project.Geometry:AddPolyline(properties)
    properties = cf.Helix.GetDefaultProperties()
    properties.Centre.N = "top-height"
    properties.BaseRadius = radius
    properties.EndRadius = radius
    properties.Height = height
    properties.Turns = turns
    helix = project.Geometry:AddHelix(properties)

    --Create Port
    port = project.Ports:AddWirePort(line.Wires[1])
    port.Location = cf.Enums.WirePortLocationEnum.End

    -- Add a Voltage source to the port
    config.Sources:AddVoltageSource(port)

    union = project.Geometry:Union({line, helix})
    union.Label = "Antenna"
    return union
end
```

- linx_antenna.lua continued

```
function setupAntennaSolutionConfiguration()
    -- Set total source power
    properties = config.Power:GetProperties()
    properties.ScaleSettings =
cf.Enums.PowerScaleSettingsEnum.TotalSourcePower
    properties.SourcePower = "10e-3"
    config.Power:SetProperties(properties)

    -- Request a 3D pattern far field result
    config.FarFields:Add3DPattern()
end
```

- linx_antenna_performance.lua

```
-- Setup and run simulations for linx whip antenna
require "linx_antenna"

app = cf.GetApplication()
project = app:NewProject()
config = project.SolutionConfigurations[1]
project.ModelAttributes.Unit = cf.Enums.ModelUnitEnum.Millimetres

constructAntenna()
setupAntennaSolutionConfiguration()

-- Define an infinite metallic ground plane
project.GroundPlane.DefinitionMethod =
cf.Enums.GroundPlaneDefinitionMethodEnum.PEC

-- Set the frequency range to discrete linearly spaced frequency
samples
properties = config.Frequency:GetProperties()
properties.End = "freq+75e6"
properties.NumberOfDiscreteValues = "11"
properties.RangeType =
cf.Enums.FrequencyRangeTypeEnum.LinearSpacedDiscrete
properties.Start = "freq-75e6"
config.Frequency:SetProperties(properties)

-- Mesh the model and run the solver
project.Mesher.Settings.WireRadius = "1e-3"
project.Mesher:Mesh()

-- Save the model and run the FEKO solver
app:SaveAs("linx_whip.cfx")
project.Launcher:RunFEKO()

project.GroundPlane.DefinitionMethod =
cf.Enums.GroundPlaneDefinitionMethodEnum.Homogeneous
project.Mesher:Mesh()
app:SaveAs("linx_whip_without_ground.cfx")
project.Launcher:RunFEKO()
```

- vine.lua

```
-- Construct a single vine
function constructVine()
    --Create Variables
    pole_radius = project.Variables:Add("pole_radius", "0.03")
    pole_height = project.Variables:Add("pole_height", "0.5")
    foliage_height = project.Variables:Add("foliage_height",
"0.8")
    foliage_bottom_width =
project.Variables:Add("foliage_bottom_width", "2")
    foliage_top_width =
project.Variables:Add("foliage_top_width", "1")
    foliage_bottom_depth =
project.Variables:Add("foliage_bottom_depth", "0.2")
    foliage_top_depth =
project.Variables:Add("foliage_top_depth", "0.1")

    --Create Media
    foliageMedium = project.Media:AddDielectric(1.03, 0.00028,
1000.0)
    foliageMedium.Label = "Foliage"
    foliageMedium.Colour = "#00A200"
    soilMedium = project.Media:AddDielectric(15.0, 0.01, 1000.0)
    soilMedium.Label = "Soil"
    soilMedium.Colour = "#4A3A00"
    woodMedium = project.Media:AddDielectric(2.0, 0.04, 1000.0)
    woodMedium.Label = "Wood"
    woodMedium.Colour = "#B6861E"

    foliageLayer = project.Media:AddLayeredDielectric({0.01},
{foliageMedium})
    foliageLayer.Label = "FoliageLayer"
    foliageLayer.Colour = "#00A200"
    woodLayer = project.Media:AddLayeredDielectric({0.01},
{woodMedium})
    woodLayer.Label = "WoodLayer"
    woodLayer.Colour = "#B6861E"

    -- Create vine geometry
    pole = project.Geometry:AddCylinder(cf.Point(0, 0, 0.01),
pole_radius, pole_height)
    pole.Label = "Pole"
    foliage = project.Geometry:AddFlare(cf.Point(0, 0, 0.5),
foliage_bottom_width, foliage_bottom_depth, foliage_height,
foliage_top_width, foliage_top_depth)
    foliage.Label = "Foliage"

    setVineMediumShell()

    union = project.Geometry:Union({pole, foliage})
    union.Label = "Vine"
```

- vine.lua continued

```
    return union
end

function setVineMediumShell()
    pole.Faces[1]:Delete()
    for key,value in pairs(pole.Faces) do
        value.Medium = woodLayer
    end
    foliage.Regions[1].Medium = project.Media:GetFreeSpace()
    for key,value in pairs(foliage.Faces) do
        value.Medium = foliageLayer
    end
end

function setupVineyardSolutionConfiguration()
    -- Define an infinite ground plane of type Soil
    properties = project.GroundPlane:GetProperties()
    properties.DefinitionMethod =
cf.Enums.GroundPlaneDefinitionMethodEnum.HalfspaceReflectionCoeff
icient
    properties.Medium = soilMedium
    project.GroundPlane:SetProperties(properties)

    --Setup the solution frequency
    config.Frequency.Start = freq

    -- Set total source power
    properties = config.Power:GetProperties()
    properties.ScaleSettings =
cf.Enums.PowerScaleSettingsEnum.TotalSourcePower
    properties.SourcePower = "10e-3"
    config.Power:SetProperties(properties)

    -- Request a near field result
    properties = cf.NearField.GetDefaultProperties()
    properties.CartesianRequestPoints.Start.U = "-2"
    properties.CartesianRequestPoints.End.U = "100"
    properties.CartesianRequestPoints.End.N = "10"
    properties.CartesianRequestPoints.Increment.U = "2"
    properties.CartesianRequestPoints.Increment.N = "1"
    properties.PointSpecificationMethod =
cf.Enums.NearFieldPointSpecificationTypeEnum.Increment
    config.NearFields:Add(properties)
end
```

- open_field_and_antenna_performance.lua

```
-- Setup and run simulations for linx whip antenna performance in
an open field
require "vine"
require "linx_antenna"

app = cf.GetApplication()
project = app:NewProject()
config = project.SolutionConfigurations[1]
project.ModelAttributes.Unit = cf.Enums.ModelUnitEnum.Metres

-- Use the same settings from the vine configuration but remove
the vine
vine = constructVine()
vine:Delete()

antenna = constructAntenna()
-- Scale the antenna to mm
antenna.Transforms:AddScale(cf.Point(), 1e-3)
-- Move the antenna next to the vine pole
antenna.Transforms:AddTranslate(cf.Point(), cf.Point(-0.04, 0,
0.001))

setupAntennaSolutionConfiguration()

-- Define an infinite ground plane of type Soil
properties = project.GroundPlane:GetProperties()
properties.DefinitionMethod =
cf.Enums.GroundPlaneDefinitionMethodEnum.HalfspaceReflectionCoeff
icient
properties.Medium = soilMedium
project.GroundPlane:SetProperties(properties)

--Setup the solution frequency
config.Frequency.Start = freq
setupVineyardSolutionConfiguration()

-- Mesh the model and run the solver
project.Mesher.Settings.WireRadius = "1e-4"
project.Mesher:Mesh()

-- Save the model and run the FEKO solver
app:SaveAs("linx_whip_in_open_field.cfx")
project.Launcher:RunFEKO()
```

- single_vine_and_antenna_performance.lua

```
-- Setup and run simulations for linx whip antenna performance
with a single vine
require "vine"
require "linx_antenna"

app = cf.GetApplication()
project = app:NewProject()
config = project.SolutionConfigurations[1]
project.ModelAttributes.Unit = cf.Enums.ModelUnitEnum.Metres

vine = constructVine()
vine.Transforms:AddTranslate(cf.Point(), cf.Point(0, 0, 0.001))

antenna = constructAntenna()
-- Scale the antenna to mm
antenna.Transforms:AddScale(cf.Point(), 1e-3)
-- Move the antenna next to the vine pole
antenna.Transforms:AddTranslate(cf.Point(), cf.Point(-0.04, 0,
0.001))

setupAntennaSolutionConfiguration()

-- Define an infinite ground plane of type Soil
properties = project.GroundPlane:GetProperties()
properties.DefinitionMethod =
cf.Enums.GroundPlaneDefinitionMethodEnum.HalfspaceReflectionCoeff
icient
properties.Medium = soilMedium
project.GroundPlane:SetProperties(properties)

--Setup the solution frequency
config.Frequency.Start = freq

-- Mesh the model and run the solver
project.Mesher.Settings.WireRadius = "1e-4"
project.Mesher:Mesh()

-- Save the model and run the FEKO solver
app:SaveAs("linx_whip_in_vineyard.cfx")
project.Launcher:RunFEKO()
```

- vine_array_and_antenna_performance.lua

```
-- Setup and run simulations for linx whip antenna within a
vineyard represented by an array of vines
require "vine"
require "linx_antenna"

app = cf.GetApplication()
project = app:NewProject()
config = project.SolutionConfigurations[1]
project.ModelAttributes.Unit = cf.Enums.ModelUnitEnum.Metres

antenna = constructAntenna()
-- Scale the antenna to mm
antenna.Transforms:AddScale(cf.Point(), 1e-3)
-- Move the antenna next to the vine pole
antenna.Transforms:AddTranslate(cf.Point(), cf.Point(-0.05, 0,
0.001))

vine = constructVine()
vine.Transforms:AddTranslate(cf.Point(), cf.Point(0, 0, 0.001))

-- Use the array feature to increase the number of vines
properties = cf.PlanarAntennaArray.GetDefaultProperties()
properties.CountU = "48"
properties.OffsetX = "2.1"
properties.Label = "LinearPlanarArray1"
properties.UniformSourceDistributionEnabled = false
-- Since the antenna is part of the model and gets copies with
the array, set the redundant antenna's magnitude close to zero
for index=2, properties.CountU do
    properties.Source[index] = {}
    properties.Source[index].MagnitudeScaling = "1e-8"
    properties.Source[index].PhaseOffset = "0.0"
end
project.AntennaArrays:AddPlanarArray(properties)

setupVineyardSolutionConfiguration()

--Setup the solution frequency
config.Frequency.Start = freq

-- Mesh the model and run the solver
project.Mesher.Settings.WireRadius = "1e-4"
project.Mesher:Mesh()

-- Save the model and run the FEKO solver
app:SaveAs("linx_whip_in_vineyard_array.cfx")
project.Launcher:RunFEKO()
```

- vine_array_and_antenna_performance.lua continued

```
config.Power.SourcePower = "1"
app:SaveAs("linx_whip_in_vineyard_array_high_power.cfx")
project.Launcher:RunFEKO()

config.Power.SourcePower = "1e-3"

-- Save the model and run the FEKO solver
app:SaveAs("elevated_linx_whip_in_vineyard_array.cfx")
project.Launcher:RunFEKO()
```