

EMERGING NETWORK TECHNOLOGIES

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Abstract

Research was carried out into three modulation techniques (ASK, QPSK, QAM). Simulink was used to evaluate the performance of each. A smart garden Zigbee wireless sensor network was designed. Riverbed Modeler was used to simulate the design and evaluate performance.

Keywords – Modulation, ASK, Amplitude Shift Keying, QPSK, Quadrature Shift Keying, QAM, Quadrature Amplitude Modulation, Simulink, WSN, Wireless Sensor Network, 802.15.4, Zigbee, Riverbed Modeler

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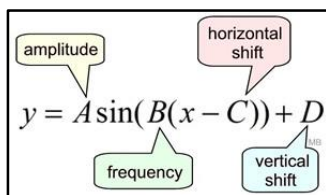
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1. Introduction

Modern communication systems use digital data. Digital data is composed of a message or signal that is made up of a series of ones and zeros. Electromagnetic waves can be used for transmission of this digital signal, but the signal needs to be modified so that the discrete states of the digital data are transmitted using an analogue high frequency carrier wave. Electromagnetic waves are sinusoidal and can be described as having three properties or characteristics:

- Amplitude
This is the maximum height of the wave.
- Frequency
This is the number of complete wave cycles in a given time period (usually 1 second).
- Phase
This is the horizontal shift or offset of a wave.

A sinusoidal wave can be represented using a mathematical formula:



The diagram shows the formula $y = A \sin(B(x - C)) + D$ with four callout boxes: 'amplitude' pointing to A, 'horizontal shift' pointing to C, 'frequency' pointing to B, and 'vertical shift' pointing to D.

Figure 1 Sine Wave Formula[1]

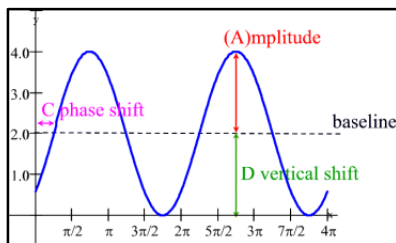


Figure 2 Sine Wave Characteristics[1]

2. Related Work and Research

By modifying the characteristics of the sinusoidal wave, the carrier wave can transmit the digital signal. The process of conversion from digital to analogue is known as Modulation. Demodulation is the process of recovering the digital signal back from the modulated analogue carrier signal.

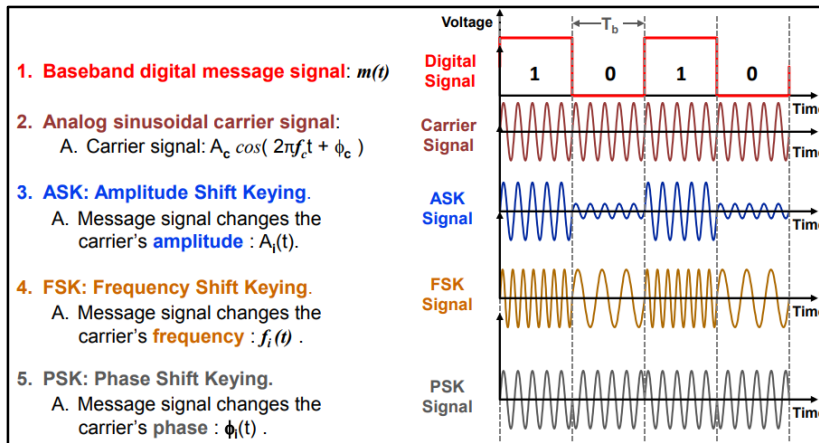


Figure 3 Modulated Wave Forms for ASK, FSK, PSK[2]

2a) Amplitude Shift Keying (ASK)

The amplitude or strength of the carrier signal is modified to represent the binary data with the frequency and phase remaining constant. Commonly, the amplitude of the carrier wave is transmitted if the signal value is 1 or reduced to zero if the signal value is 0. This form of ASK is also referred to as On-Off Keying. ASK is commonly used when transmitting data over optical fibre.

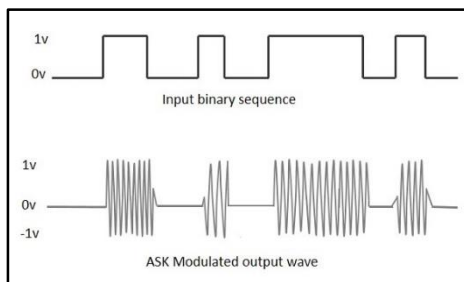


Figure 4 ASK Modulated Wave Form[3]

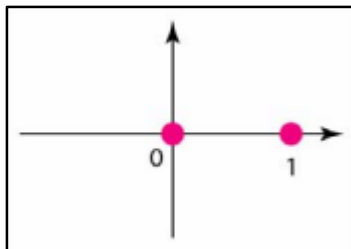


Figure 5 Constellation Diagram ASK[4]

Advantages of ASK	Disadvantages of ASK
High Bandwidth efficiency	Low Power Efficiency
Inexpensive Modulation Processes	Susceptible to noise interference

2b) Quadrature Phase Shift Keying (QPSK)

The phase of the carrier signal is modified to represent the binary data while the frequency and amplitude remain constant. Binary Phase Shift Keying (BPSK) changes the phase of the carrier signal so that the two phases in use are 180 degrees apart. QPSK uses two carrier waves, each modulated using BPSK. This results in four phases which enables transmission of two bits per symbol (00, 01, 10, 11).

The modulation process involves splitting the input signal so odd bits and even bits are separated. The even bits are combined with a carrier signal while the odd bits are combined with a similar carrier signal. However, each of the two carrier signals used are phase shifted by 90 degrees. This produces two carrier waves, each 90 degrees apart.

- I In-Phase
- Q Quadrature

These two carrier waves are used to modulate the odd and even data streams using BPSK. The two phase shifted carrier waves are then added together which results in a QPSK modulated carrier wave containing four phase shift states:

- 45 degrees
- 135 degrees
- 225 degrees
- 315 degrees

There are two possible methods to map the four symbols to the constellation diagram. Gray code maps the symbols so that any two adjacent symbols only differ in one bit. Binary code maps the symbols so that any two adjacent symbols could differ in two bits. Gray code is the preferred choice over Binary code. If noise or errors cause a receiver to map a symbol to one of its adjacent symbols there will only be one wrong bit instead of two[5].

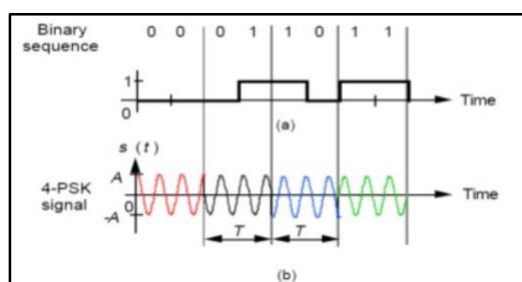


Figure 6 QPSK Modulated Wave Form[6]

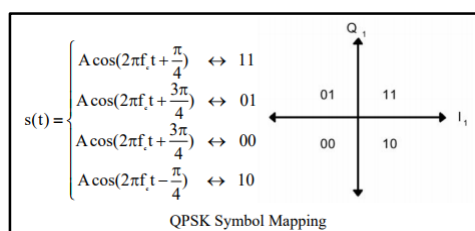


Figure 7 Symbol Mapping QPSK[7]

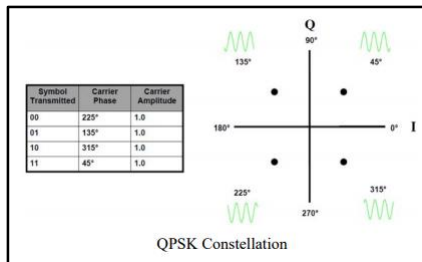


Figure 8 Constellation Diagram QPSK[7]

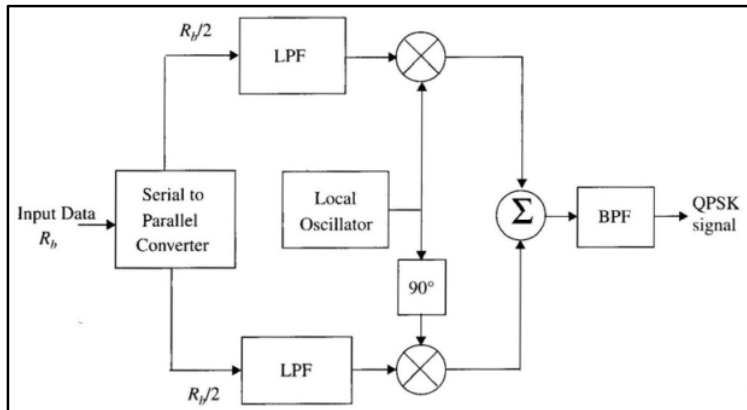


Figure 9 QPSK Modulation Block Diagram[7]

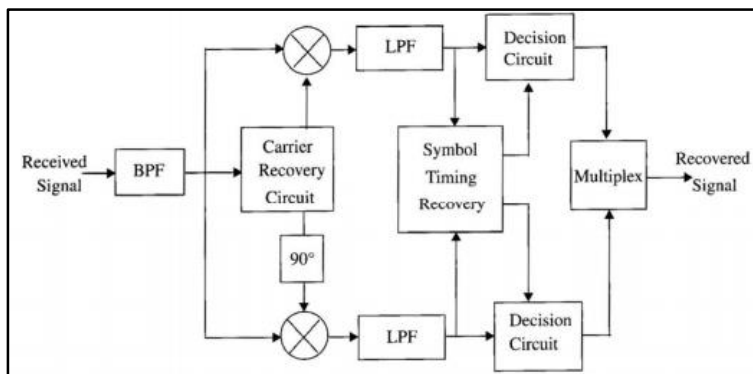


Figure 10 QPSK Demodulation Block Diagram[7]

QPSK is commonly used in wireless communication standards where high bit rate data transmission is required – LTE, 802.11 WLAN, WiMAX.

Advantages of QPSK	Disadvantages of QPSK
Higher transmission data rate than ASK (two bits per constellation)	Sensitive to phase variations. Transmitter and receiver need to be synchronised.
More efficient than ASK so uses less power	Complex demodulation algorithms

2c) Quadrature Amplitude Modulation (QAM)

QAM uses a combination of ASK and PSK where both the amplitude and the phase of the carrier signal is changed. Like QPSK, the original digital data is again split into separate streams that are phase adjusted. Each of these phase shifted carrier waves can then be further adjusted so that the amplitude changes to increase the number of bits that can be transmitted. Due to amplitude changes being susceptible to noise, there are always a higher number of phase shifts used by a QAM system than there are amplitude shifts.

There are multiple versions of QAM. Some of the common forms are:

- 16QAM (4 bits per symbol)

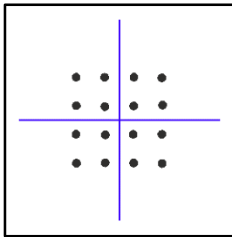


Figure 11 16QAM Constellation Diagram[8]

- 64QAM (6 bits per symbol)

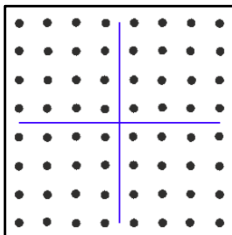


Figure 12 64QAM Constellation Diagram[8]

- 256QAM (8 bits per symbol)

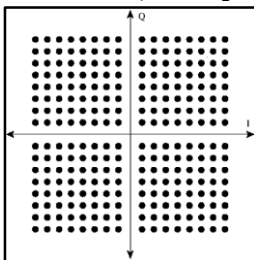


Figure 13 256QAM Constellation Diagram[9]

The numbering scheme refers to the number of states or points in the constellation[8]. For 16QAM, two carrier signals are used in a similar way to QPSK. Both have the same frequency but their phases are shifted in addition to using 2 intermediary amplitude values. Four bits per symbol are transmitted. As in QPSK, there are two methods available for symbol mapping. Gray code is the preferred method.

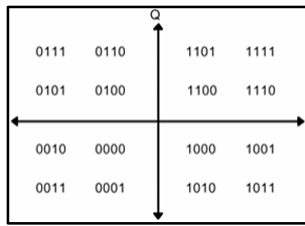


Figure 14 16QAM Symbol Mapping (Differential)[10]

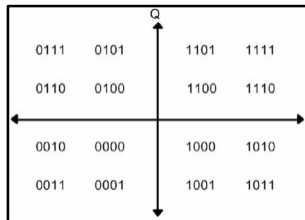


Figure 15 16QAM Symbol Mapping (Gray)[10]

QAM is commonly used in applications that require high data rates. 16QAM and 64QAM are used in Digital Video Broadcasting (DVB) in the UK for digital terrestrial TV. 64QAM and 256QAM are used in the USA for digital cable[8]. It is also widely used in high data rate wireless technologies, but is susceptible to noise interference.

Advantages of QAM	Disadvantages of QAM
Higher transmission data rate than QPSK (higher number of bits per constellation)	Sensitive to noise due to states being closer together in the constellation diagram.
	Complex receivers required to counteract noise sensitivities.

3. Simulink Models, Simulation and Results

Simulink is software that is developed by MathWorks that can be used for modelling and simulating dynamic systems.

Simulink R2017b was used to build models for the following systems:

- ASK
- QPSK
- 16QAM

Predictions were made in advance of testing and results gathering. Expectation was that as the complexity of modulation technique is increased, so too will the susceptibility to noise and interference.

Each model was run to evaluate performance across a range of noise levels. Recordings were documented and graphed. Bit Error Rate (BER) was recorded against various Signal-to-Noise Ratio (SNR) levels. Simulations were run for 100 seconds each time. Each simulation was run five times and the average of these were used for comparison purposes. The Simulink AWGN Channel Block was used to simulate the transmission medium.

SNR is defined as the ratio of signal power to noise power.

$$SNR = \frac{P_{signal}}{P_{noise}}$$

Figure 16 SNR Calculation Formula[11]

Results from the simulations were calculated using the Error Rate Calculation (ERC) Block and shown using a Display Block with 3 values. The original source signal and the received signal are fed into the ERC Block. The top value in the Display Block is the BER, the middle value is the number of incorrect bits and the bottom value is the total number of bits received.

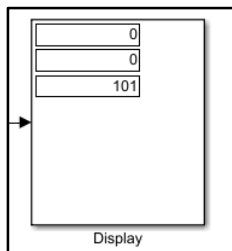


Figure 17 Simulink Simulation Display

3a) ASK Simulink Model

The ASK modulation process is a very simple process. The Bernoulli Binary Generator represents the digital source signal comprising of a series of 1's or 0's. The stream of 1's and 0's are passed into a switch. The switch either outputs a sine wave if this signal is above 0.5 or outputs a 0 if the signal is below 0.5.

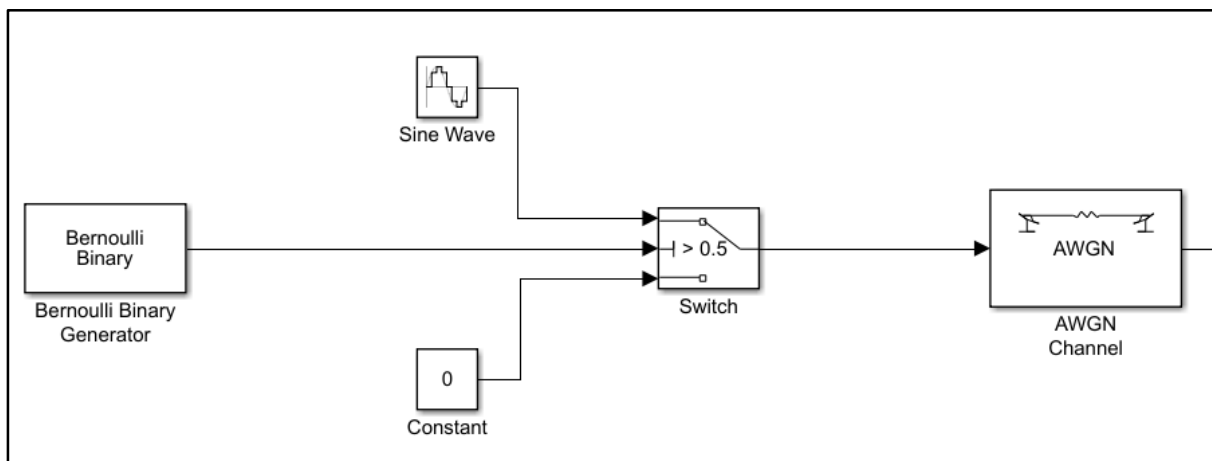


Figure 18 Simulink ASK Modulation

The de-modulation process consists of multiplying the received signal by a copy of the carrier signal. The signal is then passed through a low-pass filter and minor adjustments made to retrieve the original digital signal.

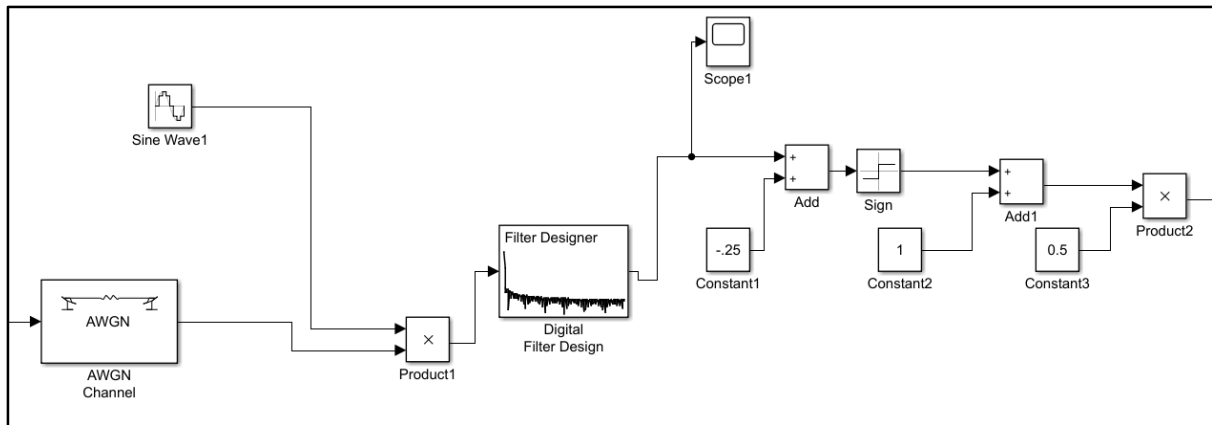


Figure 19 Simulink ASK DeModulation

3b) QPSK and 16QAM Simulink Models

QPSK and 16QAM models were built using the Matlab pre-defined Blocks.

For QPSK a random integer generator was used to output values of 0,1,2,3 to simulate the four possible symbols used. Constellation Ordering was set to Gray.

For 16QAM, the random integer generator was altered so that it output values between 0-15. M-ary Number was set to 16, Constellation Ordering was set to Gray and Normalisation Power was set to Peak, 1 watt.

Constellation Diagram Blocks were used as a visual aid to verify the transmitted output and the received output. Scopes were also used to visually check that the models were performing as expected.

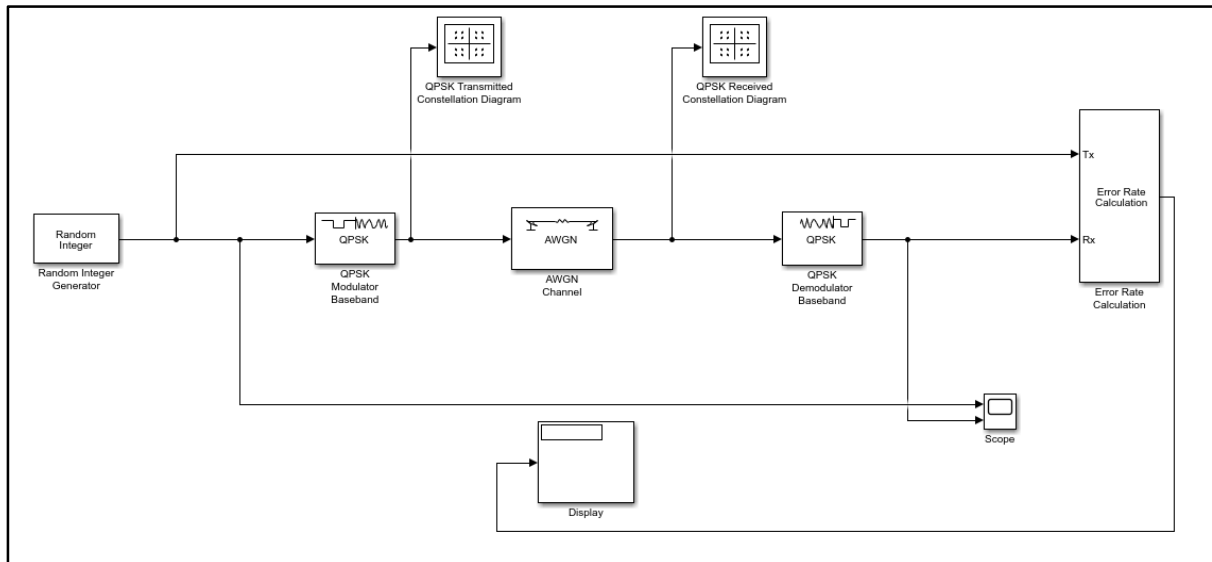


Figure 20 Simulink QPSK model

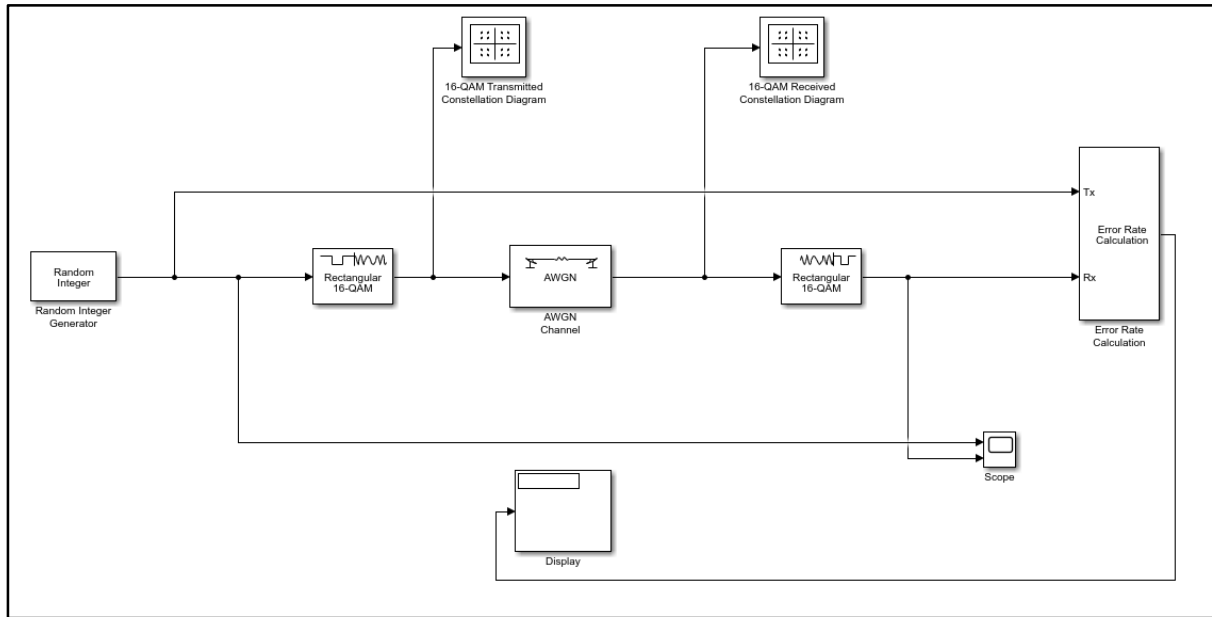


Figure 21 Simulink 16QAM model

3c) Simulink Model Results

When the Simulink models were run, the scopes showed the de-modulated signal closely matched the original source signal. The source signal is at the top and the retrieved signal after de-modulation at the bottom. Note how they are an exact match in all three modulation techniques which proves the modulation and demodulation process works as expected. A high SNR value of 30dB was used to capture these scope output samples.

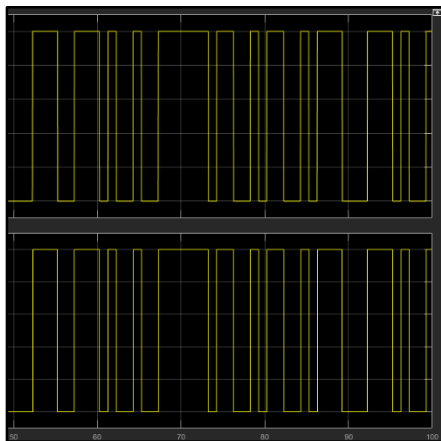


Figure 22 ASK Simulink Scope Output

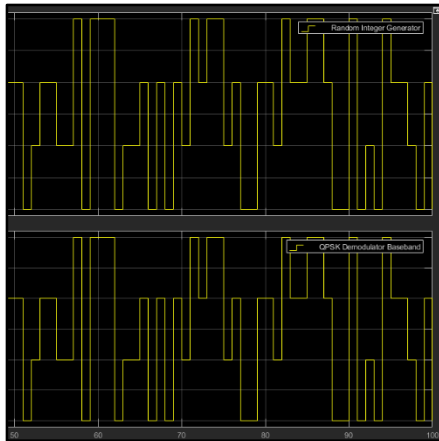


Figure 23 QPSK Simulink Scope Output

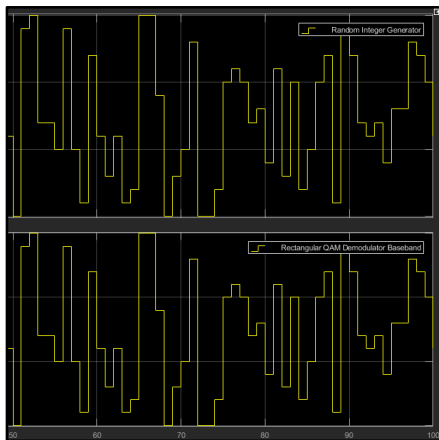


Figure 24 16QAM Simulink Scope Output

Expectation was that when adjusting the SNR value in the AWGN transmission channel, the results of the scope would change and the Error Rate Calculation results would change. The prediction was that as the SNR value was reduced closer to zero, the BER value would begin to increase. This was not the case. When using ASK errors weren't detected until the SNR value was reduced to a negative figure. As previously discussed, SNR is defined as the ratio of signal power to noise power. SNR can have either a positive or negative value if it is represented in dB scale. Signal power lower than the noise power results in a negative SNR value.

Each simulation was run across a range of SNR values and average BER values were recorded and graphed.

SNR (dB)	BER		
	ASK	QPSK	16QAM
30	0	0	0
25	0	0	0
20	0	0	0
15	0	0	0.0852
10	0	0	0.3247
5	0	0.0733	0.6377
0	0	0.2653	0.7802
-5	0	0.4435	0.8277
-10	0.0614	0.5783	0.8990
-15	0.2158	0.6535	0.9010
-20	0.3227	0.6773	0.9149
-25	0.4059	0.7406	0.9287
-30	0.4534	0.7307	0.9406
-35	0.5188	0.7604	0.9366
-40	0.5228	0.7505	0.9446
-45	0.5268	0.7565	0.9485
-50	0.5327	0.7664	0.9366
-55	0.5406	0.7723	0.9366
-60	0.5624	0.7901	0.9446

Figure 25 Simulink Results Table

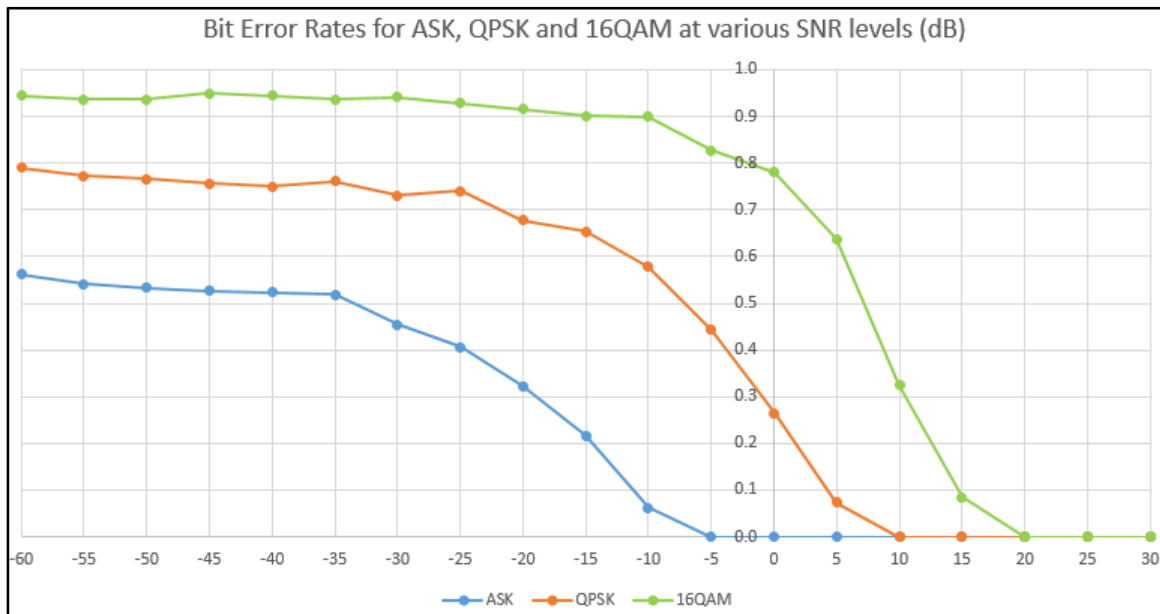


Figure 26 Simulink Results Graph

For QPSK and 16QAM, Constellation Diagrams were compared across the same range of SNR values.

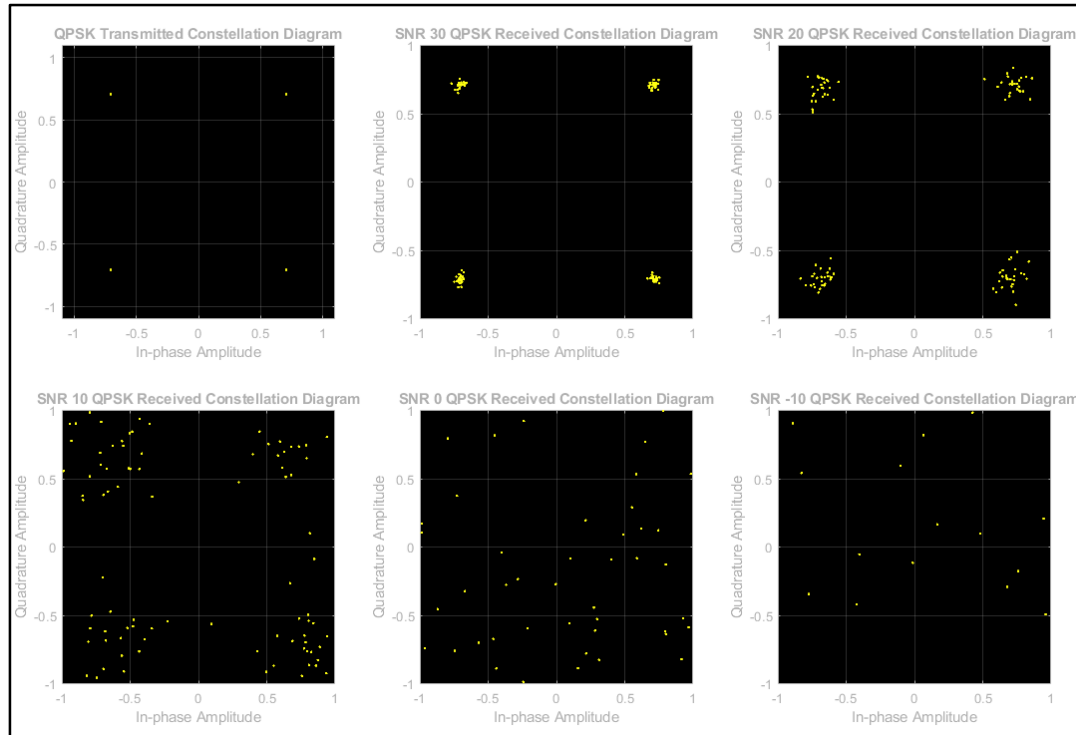


Figure 27 Simulink QPSK Constellation Diagrams across a range of SNR values

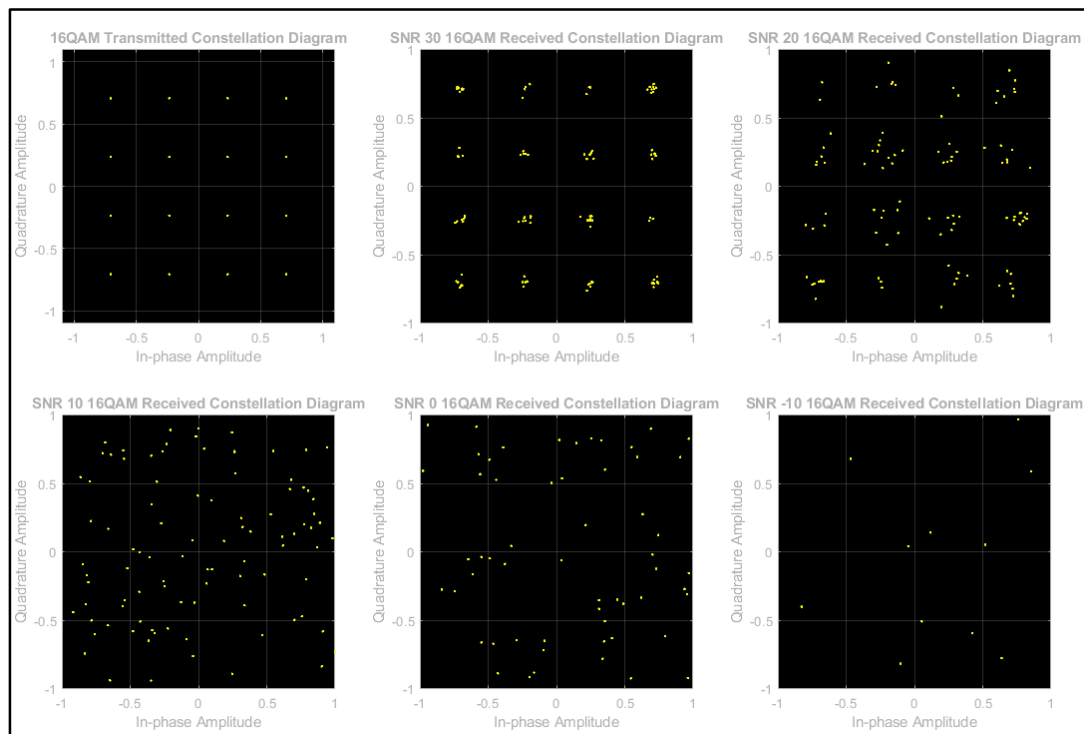


Figure 28 Simulink 16QAM Constellation Diagrams across a range of SNR values

The results from the Simulink simulations show that at high SNR levels of 30dB, all three forms of modulation performed well with zero bit-error rates. As expected, 16QAM was affected the most by a reduction in SNR value. With SNR at 10dB, QPSK and ASK were

unaffected, but 16QAM is already suffering from packet loss. The Constellation Diagram is beginning to show signs of signal interference. At increased levels of noise, or with SNR below 10dB 16QAM becomes ineffective as a means of transmission.

QPSK maintained high transmission quality even at 10dB but began to show signs of signal degradation below this level. By the time SNR drops to 0 it is also already suffering from greater than 25% packet loss. The Constellation Diagram has also become unrecognisable from the original transmission.

ASK was able to perform best at low SNR levels, even showing a BER of zero at SNR of -5dB and was only showing signs of significant signal degradation at SNR levels of below -10.

The above results show that the pre-simulation predictions were correct. As modulation complexity is increased, so too is the potential for interference by noise. Modern engineering methods allow for more complex data transmission and modulation techniques. Advances in electronics and physical modulation equipment, coding methods and complex filtering techniques have provided the means for increased data rates, over increased distances. However, there is not one 'best' modulation method. Different applications have different requirements that inevitably require different modulation techniques. Adaptive modulation builds on this by allowing systems to choose the best available modulation technique for the particular application in the current operating environment and conditions.[12]. QPSK and QAM are both used in IEEE 802.11 (Wi-Fi), 802.16 (WiMAX) and Cellular (3G, 4G & LTE) communications[13].

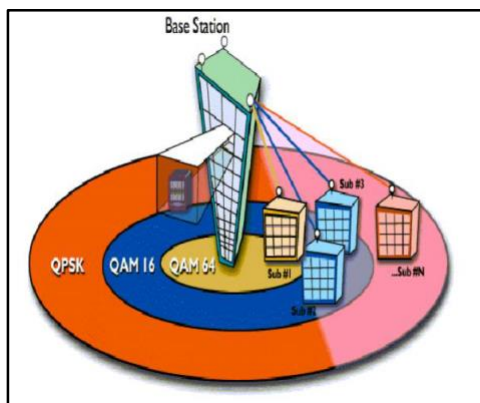


Figure 29 Distances govern modulation techniques in use[11]

4. Smart Garden Wireless Sensor Network

The University of Wales, Trinity St David are moving to a new building in the Waterfront Innovation Quarter in SA1. They require a 'Smart Garden' that provides staff, students and visitors with near real-time data regarding the weather conditions and usage status of the garden.

Wireless Sensor Networks (WSN) have become a common feature in the modern world across multiple application fields including military, agricultural, industrial, home, health and environmental sectors[14].

Zigbee is a communications protocol developed by the Zigbee Alliance intended for low-power, low-throughput, low-cost sensor networks[15]. It builds on the IEEE Standard 802.15.4 which defines the physical and MAC layers, by additionally defining the application and security layer. Provided that a device is Zigbee-compliant, then that device is capable of communication with other Zigbee-compliant devices, regardless of differing manufacturers.

Both 802.15.4 and Zigbee can work on three frequency bands:

- 868MHz Europe
- 915MHz North America
- 2.4GHz World

All three bands use Direct sequence spread spectrum (DSSS), but the 868MHz and 915MHz bands use Binary Phase Shift Keying (BPSK) and the 2.4GHz band uses offset quadrature phase shift keying (O-QPSK). CSMA (Carrier Sense Multiple Access) techniques are used to avoid transmission clashes[16].

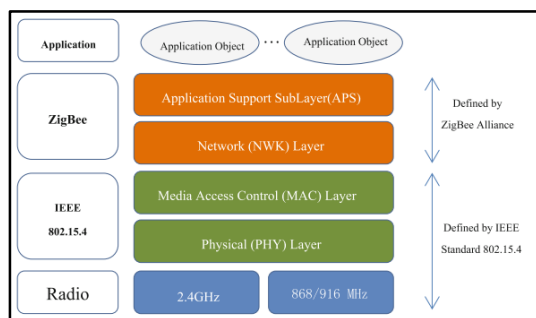


Figure 30 ZigBee protocol stack architecture[15]

OPTIONS FOR FREQUENCY ASSIGNMENTS			
Geographical regions	Europe	Americas	Worldwide
Frequency assignment	868 to 868.6 MHz	902 to 928 MHz	2.4 to 2.4835 GHz
Number of channels	1	10	16
Channel bandwidth	600 kHz	2 MHz	5 MHz
Symbol rate	20 ksymbols/s	40 ksymbols/s	62.5 ksymbols/s
Data rate	20 kbits/s	40 kbits/s	250 kbits/s
Modulation	BPSK	BPSK	Q-QPSK

Figure 31 802.15.4 Channel assignments[17]

Comparing Zigbee to some other common wireless technologies, it is clear that it is the most suitable technology for wireless sensor networks with particular strengths being power consumption, durability, scaling and cost[18].

Features	GPRS/ GSM	Wi-Fi	Bluetooth	Zigbee
Focusing area	Wide range of audio and data	Web, email, Video	Instead of cable	Monitoring and control
System resource	16 Mb+	1 Mb+	250Kb+	4-32 Kb
Battery life(day)	1-7	0.5-5	1-7	100- 1000+
Network size	16 Mb+	32 Mb	7 Mb	~ Infinite (2 ⁶⁴)
Network data width(kb/sec)	64 – 128+	11000-54000	720	100- 1000+
Range (meters)	1000+	1-100	1-10+	1 – 100+
Success areas	Accessibility, quality	Speed, flexibility	Cost, convenience	Durability, cost, power consumption

Figure 32 Comparison of Zigbee with other common wireless technologies[18]

Zigbee devices fall under three categories:

- Coordinator
A Coordinator device is responsible for initial sensor network formation and then acts as a router device
Only one coordinator per wireless sensor network
Required to be always on and available
- Router
Provide routing services to end devices
Can also act as an end device
Does not enter sleep mode
- End Device
Cannot relay messages from other devices
Can enter sleep mode to conserve power

Zigbee networks can be configured using three potential topologies:

- Star

Star topology is the simplest method of designing a wireless sensor network

There is one coordinator and the end devices and routers can only communicate directly to it. There is no relaying of information through router devices.

There is no redundancy or resilience in the design

All network packets must travel through the coordinator which has the potential to result in network congestion.

Coordinator is the parent and all other devices are its children.

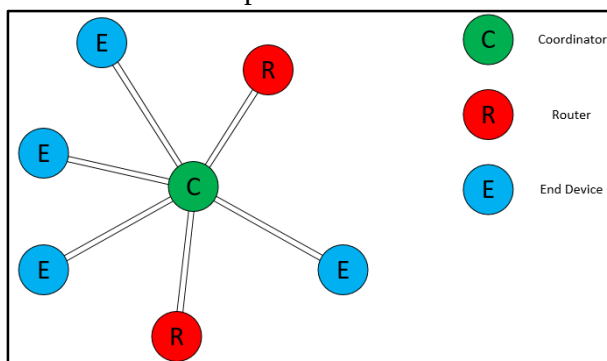


Figure 33 Zigbee Star Topology

- Tree

Tree topology connects the coordinator with end devices and routers. The difference from the star topology is that a router device can have its own child devices.

There is no redundancy or resilience

Potential for network congestion is reduced because a child will only communicate with its parent.

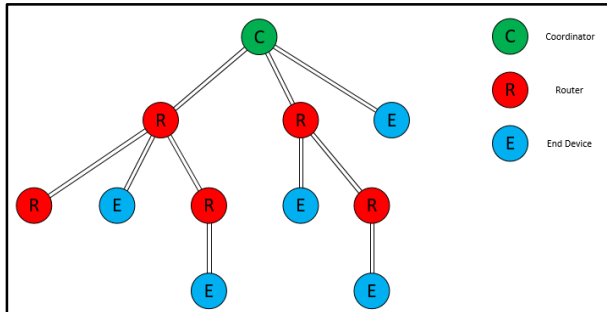


Figure 34 Zigbee Tree Topology

- Mesh

Mesh topology allows router devices to determine the best routes for communication between themselves. This provides redundancy and resilience. If a router device is unavailable, then an alternate routing path is found. A mesh topology is self-configuring and self-healing.

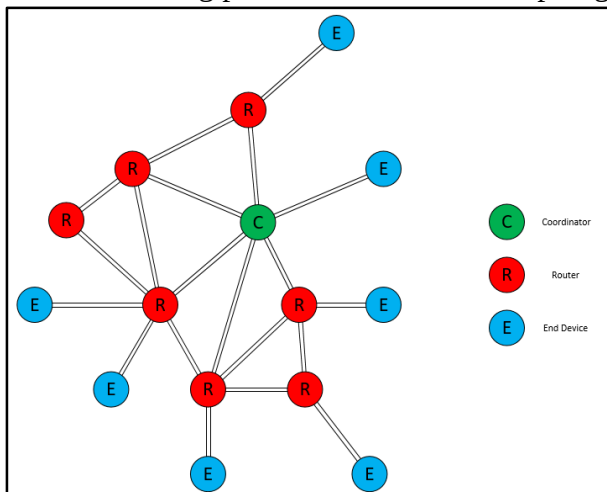


Figure 35 Zigbee Mesh Topology

A Zigbee gateway is required to link the wireless sensor network to the internet or LAN. Zigbee gateways can come in many formats, ranging from a Zigbee USB device that is plugged in to a PC/Server or a wired/wireless bridge device. For this design a Cisco router device was the preferred option as it meets the existing switch manufacturer standard that is used within the UWTSD building for corporate LAN use. Cisco offer a number of options for a Zigbee Gateway.

- Connected Life Gateway (CLG-8202-WW)

Seems to be targeted at home/small business users

Can be wall mounted only

No option for IP55 rating – needs to be situated internally

No PSU redundancy

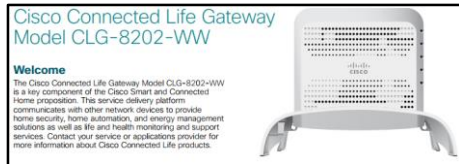


Figure 36 Cisco Zigbee Gateway - CLG-8202-VW[19]

- Cisco Smart+Connected Controller 800
Can be rack mounted
No option for IP55 rating – needs to be situated internally
No PSU redundancy



Figure 37 Cisco Zigbee Gateway - Smart+Connected Controller 800[20]

- Cisco Industrial Router 910 (IR910-K9)
Has an open slot allowing addition of a Zigbee interface card
Local computing capability (Cisco proprietary Fog computing platform)
Supports C/C++, Python, and Java
Optional local SSD storage
PSU Redundancy – dual power inputs



Figure 38 Cisco Zigbee Gateway - IR910 with IP55 enclosure[21]

After reviewing the available options from Cisco, the IR910 was deemed to be the most suitable for this smart garden project. This switch runs Cisco's IOx operating system and complies with the Cisco Fog Computing concept that allows data to be processed and executed locally at the network edge. This offloads computing pressure from the UWTSD corporate servers and reduces bandwidth consumption on the UWTSD corporate LAN. Cisco's Fog Computing concept is particularly suited to applications that fall under the Internet of Things (IoT). It is the opposite of Cloud computing where data is sent to a remote location for processing and analysis. Similar to Cloud, Fog provides data, compute, storage, and application services to end-users, but these services occur in close proximity to the end users[21].

This device will act as the Zigbee controller. It will be externally wall mounted using the IP55 housing, will use dual PSU cables and be connected to the UWTSD LAN via outdoor rated Ethernet cable.

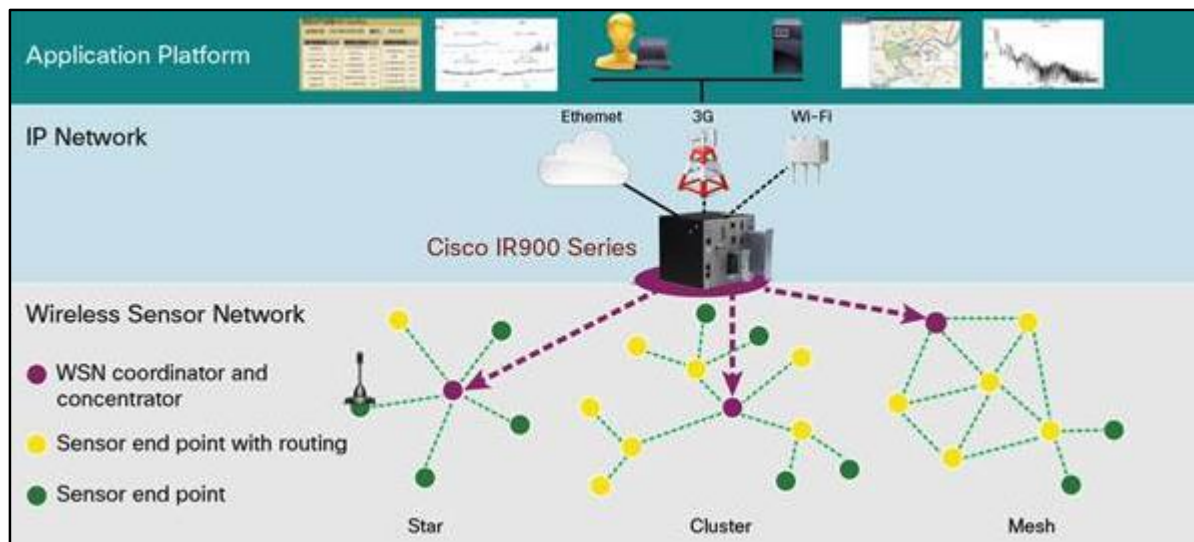


Figure 39 Zigbee Topologies with CiscoIR900 Series as the Zigbee Controller[21]

The smart garden at UWTSD is an enclosed space that occupies an area that is approximately 400 square metres (20m x 20m). It will have the following 11 sensors:

- 1 x UV
- 1 x Temperature
- 1 x Humidity
- 1 x Wind Speed/Direction
- 2 x Occupancy/Motion Detection
- 4 x Pressure pads (mounted under the benches)
- 1 x Door contact

The initial design only contains 11 sensors, but due to the scalability potential that Zigbee provides, UWTSD could easily further develop their Smart Building with additional sensors in different locations at a later stage.

Cisco Fog Director is an application that Cisco provide to enable management of IOx devices and Fog applications[22]. This will be installed on a physical server that is rack mounted in the UWTSD data services room.

Another physical web application server will be rack mounted in the same data services room. This will allow the IR910 router to upload data gathered from the smart garden for viewing by staff, students and visitors. This method will reduce bandwidth on the UWTSD corporate LAN. Instead of a constant stream of data being uploaded to the web server, the IR910 will be configured to upload data at given regular intervals. This could initially be set at 5 minutes but could be adjusted up or down as required.

A Cisco ASA 5506-X w/ FirePOWER Services firewall will be situated between the IR910 and the edge switch that gives connectivity to the UWTSD corporate LAN to both protect the WSN from the corporate LAN and the corporate LAN from the WSN.

A video display unit will be situated in the Reception/Foyer area to display near-real time data about the Smart Garden. Historical data and reporting tools will also be available to certain user groups by accessing the web server via the UWTSD Intranet.

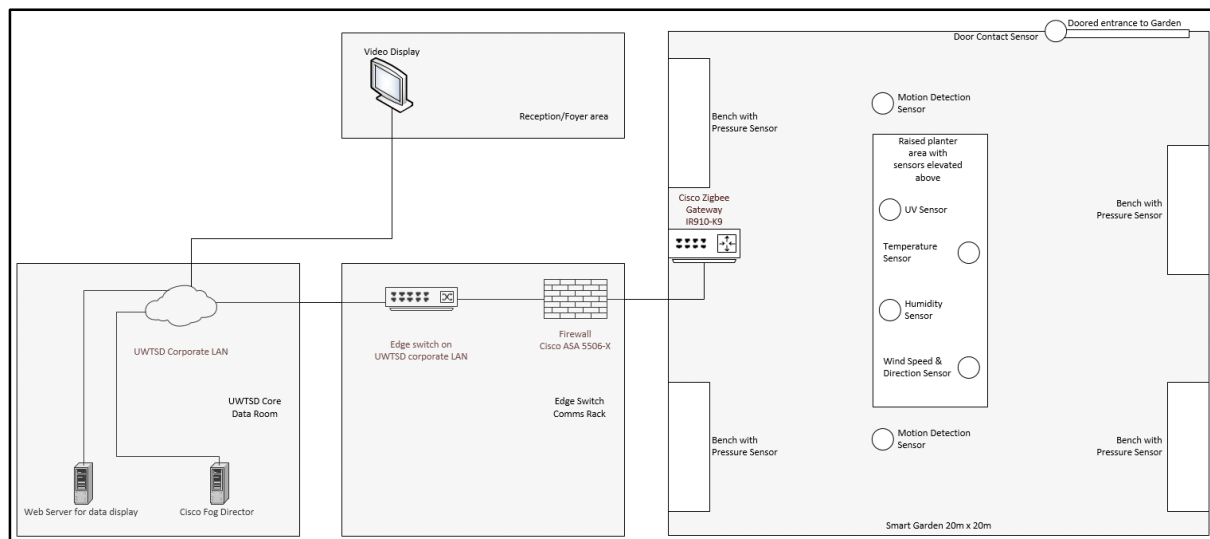


Figure 40 Smart garden topology diagram

5. Riverbed Simulation of Smart Garden WSN

Using Riverbed Modeler Academic Edition 17.5, the three different Zigbee topologies will be evaluated for performance. Parameters used for evaluation will be delay and packet loss. Only the communications between the Zigbee Controller and the Zigbee devices will be looked at. Due to the network design chosen and the use of the Cisco IR910 router with Fog Computing, data gathering, processing and analysis will be done by the Controller itself which results in a reduction in network traffic beyond the Cisco IR910.

A new project was created with a different scenario for each topology method.

Manage Scenarios			
Project name: JPWSN			
#	Scenario Name	Saved	Results
1	StarTopology	saved	up to date
2	TreeTopology	saved	up to date
3	MeshTopology	saved	up to date

Figure 41 Riverbed Project and Scenarios

Each scenario contained the same number of nodes, but the configuration of the nodes differed in the three scenarios. The physical location of each node within the network stayed the same. This was due to the geographical constraints of the garden that required sensors to be in specific pre-determined areas.

Common scenario configuration parameters were used across all scenarios.

Attribute	Chosen setting
ACK Mechanism	Enabled with Default Settings
CSMA-CA Parameters	Default Settings
Channel Sensing Duration	0.1
Data Rate	Auto Calculate
Destination	Parent
PAN ID	Auto Assigned
Packet Inter-arrival Time	Constant(1.0)
Packet Reception-Power Threshold	-85
Packet Size	Constant (1024)
Start Time	Uniform (20,21)
Stop Time	Infinity
Transmission Bands	All
Transmit Power	0.05

Figure 42 Common configuration parameters across the three scenarios

Star Topology Scenario

- 1 Fixed Zigbee Coordinator Node
- 11 Fixed Zigbee End Device Nodes
- Network Parameters setting of Coordinator was set to Default Star Network

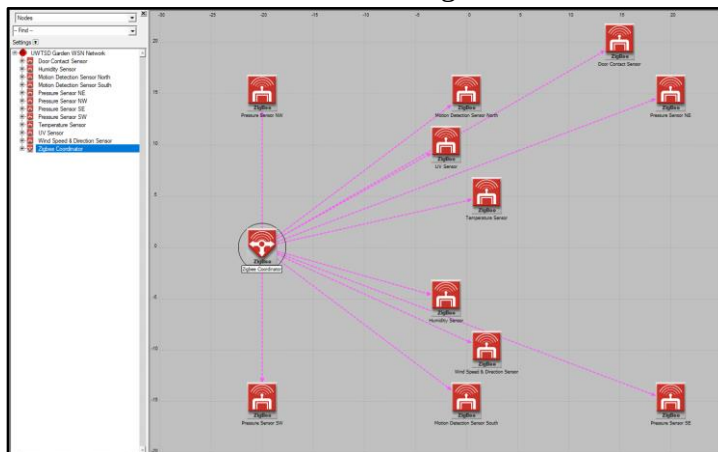


Figure 43 Riverbed star topology layout

Tree Topology Scenario

- 1 Fixed Zigbee Coordinator Node
- 6 Fixed Zigbee Router Nodes
- 5 Fixed Zigbee End Device Nodes
- Network Parameters setting of Coordinator was set to Default Tree Network

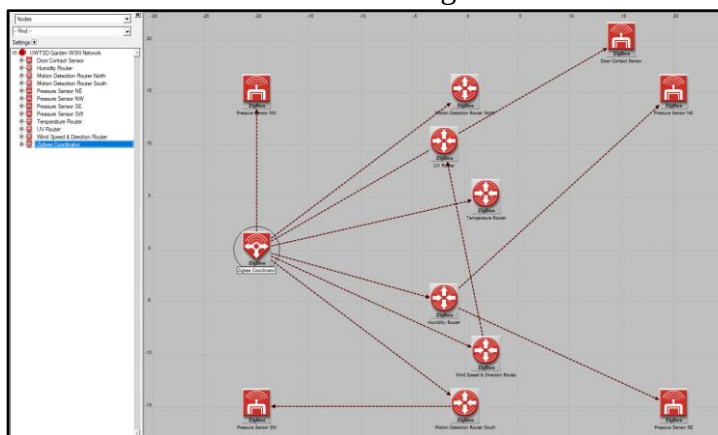


Figure 44 Riverbed tree topology layout

Mesh Topology Scenario

- 1 Fixed Zigbee Coordinator Node
- 6 Fixed Zigbee Router Nodes
- 5 Fixed Zigbee End Device Nodes
- Network Parameters setting of Coordinator was set to Default Mesh Network

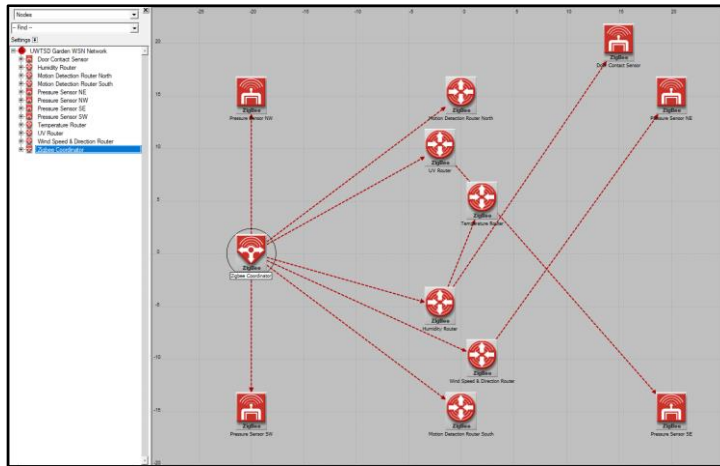


Figure 45 Riverbed mesh topology layout

The following metrics were collected

- Global Statistics
 - Zigbee 802.15.4 MAC
 - Delay (sec)
 - Throughput (bits/sec)
 - Zigbee Application
 - End-to-end Delay (seconds)
 - Zigbee Network Layer
 - Packets Dropped (Not Joined) (packets)

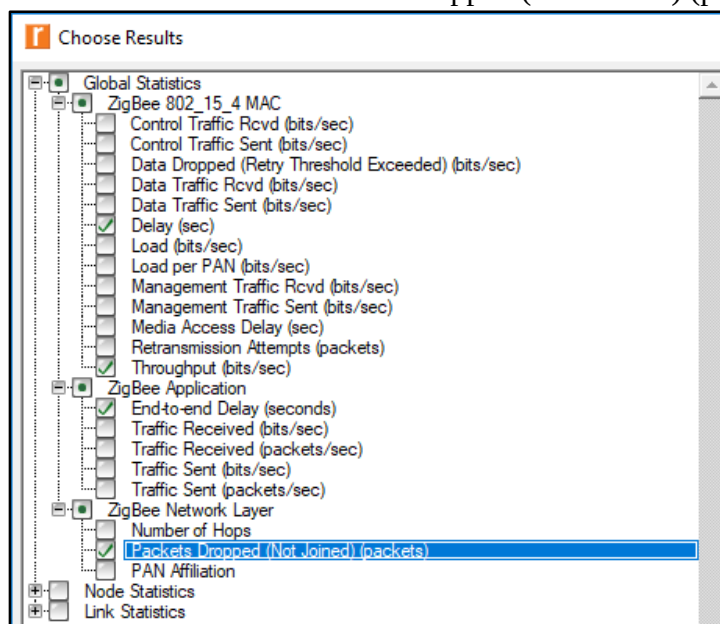


Figure 46 Riverbed simulation metrics

Each simulation was run for 2 hours, Network Formation Threshold was set to 30 seconds and Report Snapshot time was set to 3600.

Attribute	Value
ZigBee	
Network Formation Threshold (seconds)	30
Report Snapshot Time(s)	3600

Figure 47 Riverbed simulation reporting parameters

6. Riverbed Simulation Results and Analysis

The three different scenarios were run and data collected. Using the reporting tools within Riverbed, graphs of each of the chosen metrics were exported.

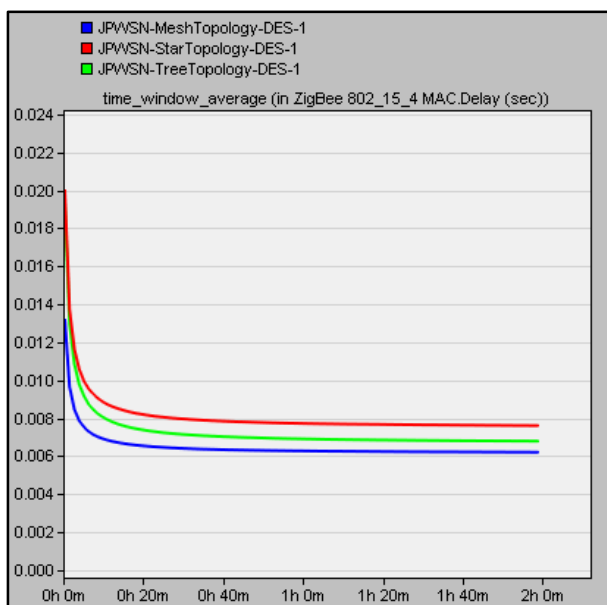


Figure 48 Riverbed graph showing Delay (sec) for three Zigbee topology designs

Figure 48 shows delay (sec) quickly drops to a steady level across all topologies. Mesh is the topology that has the lowest delay, with Star having the highest level.

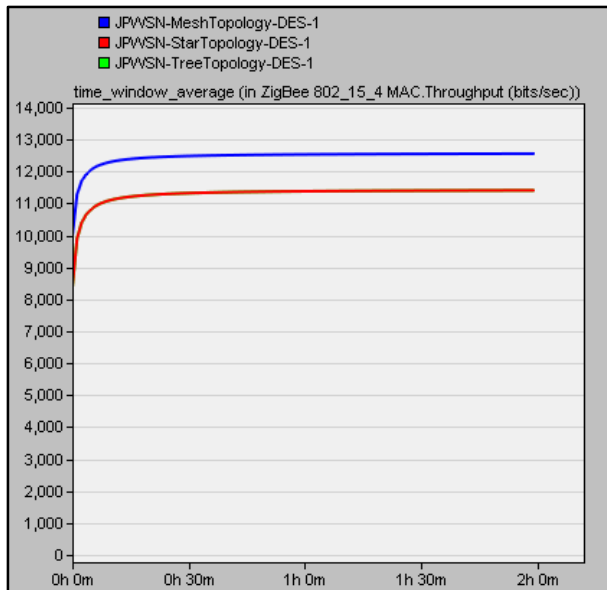


Figure 49 Riverbed graph showing Throughput (bits/sec) for three Zigbee topology designs

Figure 49 shows throughput (bits/sec) for each topology. Again, Mesh is the topology to have the highest throughput. It's not easy to see on the graph, but Star and Tree topologies have nigh on exactly the same throughput. The green line is not fully visible due to the red line overlaying it.

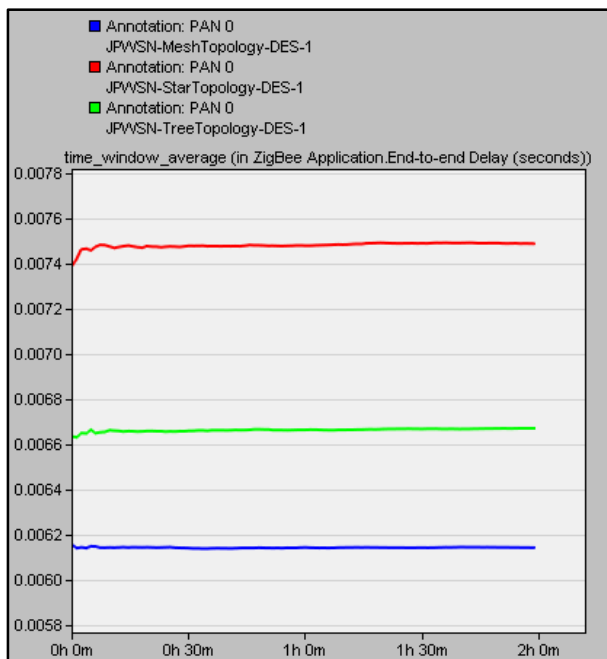


Figure 50 Riverbed graph showing End-to-end Delay (seconds) for three Zigbee topology designs

Figure 50 shows End-to-end delay was significantly lower for Mesh than both Tree and Star topologies.

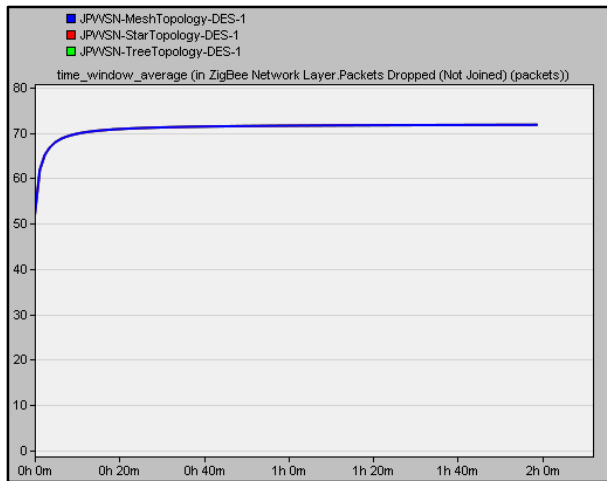


Figure 51 Riverbed graph showing Network Layer Packets Dropped (not joined) (packets) for three Zigbee topology designs

Figure 51 shows all three topologies have nigh-on exactly the same levels of Layer packets dropped (not joined)(packets)

From the above simulations and results, it is clear that Mesh topology is the preferred topology design when implementing a Zigbee WSN.

It was then decided that an additional test would be attempted. In the Star, Tree and Mesh scenarios above, the Transmission Band was set to All. The Mesh scenario was replicated into two new scenarios and the Transmission Bands were set to Europe and Worldwide. The new additional scenarios were run, data collected and graphs of the same original metrics were exported.

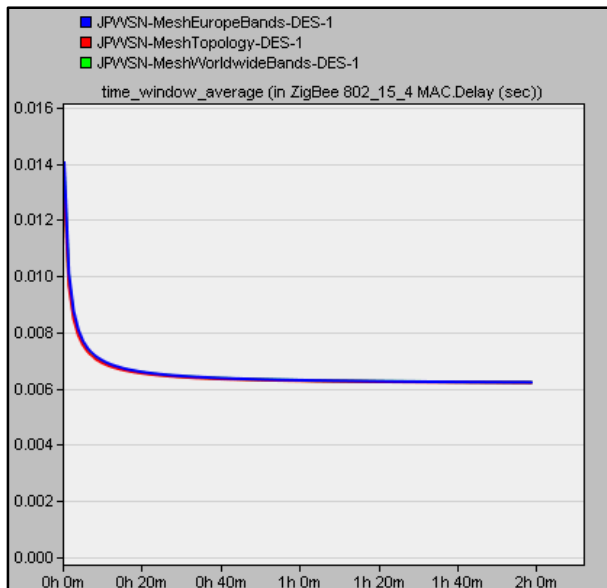


Figure 52 Riverbed graph showing Delay (sec) for Mesh topology with three different Transmission Bands used

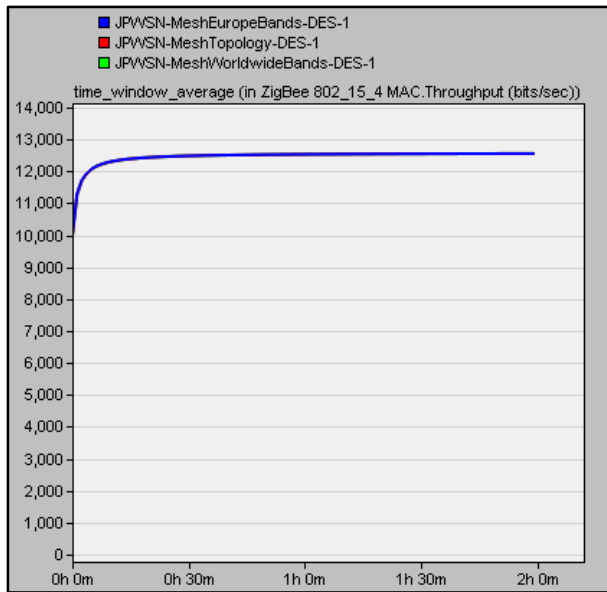


Figure 53 Riverbed graph showing Throughput (bits/sec) for Mesh topology with three different Transmission Bands used

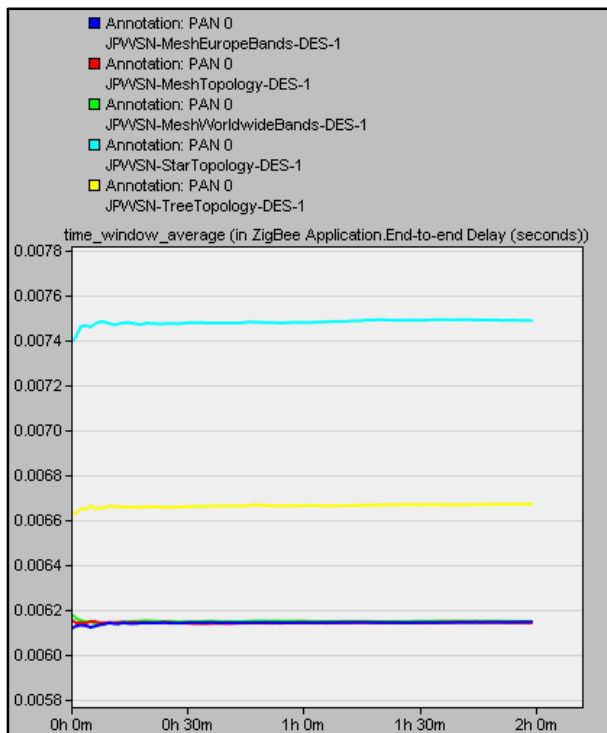


Figure 54 Riverbed graph showing End-to-end Delay (seconds) for three Zigbee topology designs and mesh topology with three different Transmission Bands used

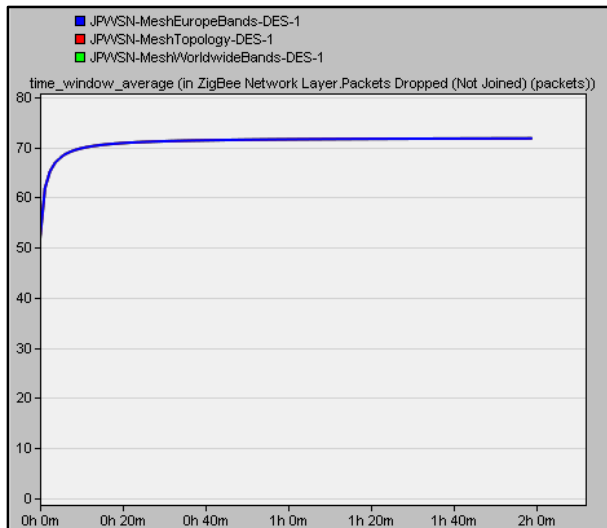


Figure 55 Riverbed graph showing Network Layer Packets Dropped (not joined) (packets) for Mesh topology with three different Transmission Bands used

These additional tests didn't give any noticeable differences in results. For this particular model, there was no difference in simulation results when changing Transmission Bands from All to Worldwide or Europe.

Limitations of the Riverbed Simulation software, meant that it was not fully possible to carry out the full range of testing that was initially planned. It is possible to 'fail' a node and run the simulation again. The software then finds alternative routes for traffic to continue flowing. However, there doesn't seem to be a way of 'failing' a node part way through a simulation. Failing a node in Star mode, resulted in that particular sensor node being unavailable. Failing a router node in Tree mode meant that it was unavailable, but because the simulation was running from the beginning, all other end nodes routed via alternate router nodes. The same happened in Mesh mode. Mesh mode only showed one path to the Controller, when expectation was that it would show multiple available paths. Expected results if this feature was available would be that a router node could be 'failed' during the simulation and the mesh Zigbee network would self-heal and nearby nodes would connect to an alternate router to maintain connectivity.

Simulation time was set to 2 hours for each scenario. Zigbee WSN are designed to be installed and remain operating for long periods of time. As outlined in figure 32, battery life in Zigbee sensors run in the 100-1000+ days range. A longer simulation time would give more reliable and accurate results when modelling a real-life example of a Zigbee WSN. However, for reasons that remain undetermined, Riverbed Modeler Academic Edition 17.5 always completed simulation when it reached 50,000,002 events – regardless of the duration of simulation time that has been processed.

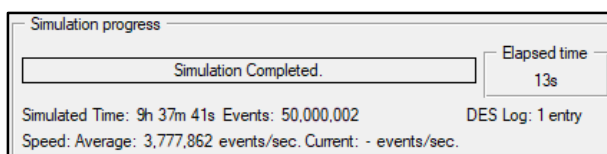


Figure 56 Riverbed simulation complete after 50,000,002 events

Further simulation works that would be beneficial would be to adjust some additional parameters within the WSN network. Some additional options for future simulations could include:

- Additional number of sensors
- Increasing the physical size of the garden area (instead of a walled garden, maybe a large open area that stretches across a vastly greater geographical location)
- Extending the WSN to include other systems within the UWTSD building – heating, ventilation, utility meters, renewable energy meters, classroom occupancy etc.

When designing the WSN, consideration was given to ensuring potential for future changes, amendments and extension of the network. The WSN design proposed only had 11 sensors, but Zigbee networks can have many thousands of nodes. For this design, mesh topology was determined to be the greatest performing topology across all metrics used. The benefits of using a mesh topology include the ability for the network to self-configure and self-heal but also allows for future expansion of the WSN if UWTSD decided this was something that they required.

7. Conclusion

Part 1 documented research that was undertaken regarding three different modulation techniques (ASK, QPSK and QAM). These modulation techniques were then modelled using Simulink and performance was evaluated. Part 2 documented design of a WSN for a smart garden at the new UWTSD building at SA1. Zigbee was the chosen protocol. Research was carried out into Zigbee WSN's and a proposed network design was documented. Riverbed Modeler was used to simulate the Zigbee WSN. Three topology designs were evaluated (Star, Tree, Mesh). For this design, mesh topology was determined to be the greatest performing topology across all metrics used. Additional tests were undertaken to see if any performance changes were brought about by changing the Transmission Band, but this didn't seem to have any impact.

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