HYBRID OPTICAL AND WIRELSS BROADBAND ACCESS NETWORK OPTIMISATION AND SURVIVABILITY

By

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A thesis submitted to the Department of Electronic Engineering,
Faculty of Engineering and Green Technology
Universiti Tunku Abdul Rahman,
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy in Engineering
Nov 2018

ABSTRACT

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Deployment of redundant components is the ubiquitous practice in improving the reliability and survivability of a network due to node and link failures. Extensive studies have been done to evaluate the impact of node failure and provision of redundant resources in specific segment of Hybrid Optical and Wireless Broadband Access Network to resolve the issues on network cost and survivability. However, methodology that enable the evaluation and decision to prioritise the deployment of redundant facilities in the network to ensure network survivability has not been explored. This research work was done to fill this germane gap and to investigate the impact of the critical segment on the network deployment cost and survivability. The results obtained using FMEA technique showed that the backup power is the most critical component required to be put in place at the front end of a hybrid optical and wireless broadband access network particularly in the least developed countries where broadband growth is essential for improving the economy of the nations. The simulation results showed that the deployment cost for the front end using alternative path network with backup power can be reduced by up to 34% with less than 2% of degradation in network survivability compared to a full survivability network. The findings and algorithm developed from the research work is able to assist potential investors to evaluate the investment

cost in particular the backup power to mitigate the problem of unreliable electricity supply particularly in the rural and least developed countries where approximately 1.2 billion people are still not connected to the Internet.

ACKNOWLEDGEMENT

I would like to express my sincere appreciation and gratitude to my supervisor; Dr. Lee Sheng Chyan and my co-supervisor Dr. Yeong Kee Cheong their helpful discussions and suggestions. I am grateful to Dr. Tan Su Wei from Iconix Consulting for his invaluable advice and support. I would like to thank all those who have given their assistance and encouragement.

APPROVAL SHEET

This dissertation/thesis entitled "**HYDBRID OPTICAL AND WIRELESS BROADBAND ACCESS NETWORK OPTIMISATION AND SURVIVABILITY**" was prepared by CHAN CHEONG LOONG and submitted as partial fulfillment of the requirements for the degree of Doctor of Philosophy in Engineering at Universiti Tunku Abdul Rahman.

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SUBMISSION OF THESIS

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DECLARATION

I hereby declare that the dissertation is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTAR or other institutions.

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LIST OF ABBREVIATIONS

ADSL	Asymmetrical Digital Subscriber Line
AON	Active Optical Network
APD	Avalanche Photodiode
ARPU	Average Revenue Per User
AWG	Arrayed Waveguide Gratings
BPON	Broadband PON
CAPEX	Capital Expenditure
CEPT	European Conference of Postal and Telecommunications Administrations
CO	Central Office
CP	Customer Premise
CSMA-CD	Carrier Sense Multiple Access / Collision Detection
DSL	Digital Subscriber Line
ECC	Electronic Communication Committee
EIA	Electronic Industries Alliance
EIRP	Effective Isotropic Radiated Power
eNB	Evolved Node B
EPC	Evolved Packet Core
EPON	Ethernet PON
FATTN	Fibre-or-Air-to-the-Node
FCC	Federal Communications Commission
FFT	Fast Fourier Transform
FMEA	Failure Mode Effect and Analysis

FSL	Free Space Loss
FTTB	Fibre To The Building
FTTC	Fibre To The Curb
FTTE	Fibre To The Exchange
FTTH	Fibre To The Home
GDP	Gross Domestic Product
GNI	Gross National Income
GPON	Gigabit PON
ICT	Information and Communications Technology
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse Fast Fourier Transform
IFI	Inter Frame Interference
ILP	Integer Linear Programming
ISI	Inter-Symbol Interference
ISM	Industrial, Scientific and Medical
ISO	International Organization for Standardization
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
ITU-T	ITU Telecommunication Standardization Sector
LED	Light Emitting Diode
LOS	Line Of Sight
LP	Linear Programming
LTE	Long Term Evolution
LTE-A	Long Term Evolution - Advanced

MAC	Media Access Control
MCMC	Malaysian Communications And Multimedia Commission
MDG	Millennium Development Goal
MILP	Mixed Integer Linear Programming
MIP	Mixed Integer Programming
MTBF	Mean Time Between Failure
MTTR	Mean Time To Repair
NGPON	Next Generation Passive Optical Network
OECD	Organisation for Economic Co-operation and Development
OLT	Optical Line Terminal
ONU	Optical Network Unit
OPEX	Operating Expenditure
OTDR	Optical Time-Domain Reflectometer
P2P	Point to Point
PIN	Positive-Intrinsic-Negative
PMD	Polarization Mode Dispersion
PMP	Point to Multi-Point
POCAM	Partially Overlapped Channel Assignment
PON	Passive Optical Network
PPA	Pacific Power Association
QoS	Quality Of Service
RBS	Radio Base Station
RPN	Risk Priority Number
SAIDI	System Average Interruption Duration Index

SDG	Sustainable Development Goals
SIEPON	Service Interoperability in Ethernet Passive Optical Network
SINR	Signal to Interference Ratio
SLA	Service Level Agreement
SNR	Signal to Noise Ratio
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TIA	Telecommunication Industry Association
UNESCO	United Nations on Educational, Scientific and Cultural Organization
UNII	Unlicensed National Information Infrastructure
VDSL	Very High Bit-Rate Digital Subscriber Line
WDM	Wavelength division multiplexing
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless local area network
WMN	Wireless Mesh Network
XGPON	10 Gigabit PON

CHAPTER 1

INTRODUCTION

1.1 Research Background

It has been highlighted in United Nations (2015a) and Broadband Commission for Sustainable Development (2016) that broadband availability can contribute to the significant achievement in targets set for the 17 sustainable development goals (SDG) adopted by United Nations in 2015 to end poverty, protect the planet and ensure prosperity for all by year 2030. Broadband will also play an integral role in human development. Cities dwellers account for 54% of the world population living in cities, which consist of only 2% of the land area (Liu, et al., 2014). Broadband can enable more efficient use of energy and resources through smart grid and other smart city initiatives (ITU-T, 2015). Reports have consistently reflected the close correlation between national Gross Domestic Product (GDP) and broadband availability (ITU, 2012, Michael, 2016). Broadband access has great potential in enabling those in the remote and under-developed countries to be connected and potentially opening up work opportunities and boosting income. These merits have intensified the growth of the broadband access in all the continents in the world thus putting further pressure on the frequency spectrum available to support the rising demand.

ITU statistics (ITU, 2012) indicated the demand for wireless communication is rising on exponential curve. This is confirmed by the same rising trend in the growth of the number of broadband enabled devices such as mobile phone and tablets. The continued down trend in the prices of broadband access and the supporting communication devices will further spurred the demand for wireless communication. As the number of clients and services in the wireless communication has always been limited by the scarce radio spectrum, it requires the support of the vast bandwidth available from the optical communication network. Optical fibre broadband technology, which has the capacity to carry high volume of traffic at extremely high speed, is the obvious choice to fulfil the high demand for spectrum. However its implementation cost and time have inhibited the widespread installation especially at the front end of the broadband access network. Studies have suggested that a hybrid optical and wireless broadband access network (HOWBAN) that incorporates a high speed optical fibre network at the backend and a wireless network at the front end would be primed to provide a compromise to the market pressure (Sarkar et al., 2007a; Zheng et al., 2009). Wireless mesh network (WMN) with self-healing characteristics using Wi-Fi technologies and its relatively short set up time and comparatively lower deployment cost has been identified as a suitable candidate to support the fibre backbone in providing front end connections to quench the demand of the continued increase in mobile clients to be communicated anytime and anywhere.

1.2 Objectives

Minimising the network deployment cost is essential for successful acceptance of HOWBAN (Filippini and Cesana, 2010) however; the ability to ensure that the network can continue to function during failure is equally important (Ghazisaidi et al., 2009). The introduction of high bandwidth technologies such as Next Generation Passive Optical Network (NGPON), LTE-A (Long Term Evolution – Advanced) and 5G (Fifth Generation) Cellular Network with 10 times higher bandwidth and in particular IEEE802.11ac Wi-Fi standard will increase the number of clients that can be served by the nodes in HOWBAN. The failure of the network component will affect more mobile clients (MC) compared to the previous technologies. Reliability and survivability of HOWBAN is thus becoming more critical and urgent. While availability of a system is the ratio of time it is expected to provide the required function, reliability is the probability that the system will remain operational (Federal, 2006). On the other hand, survivability is the ability of the system to continue to provide the services even it encounters failure. Deployment of redundant components is the ubiquitous practice in improving the reliability and survivability of a network due to node and link failures. One of the objectives of this research is to find a tool that can enable the evaluation and decision to prioritise the deployment of redundant facilities in the network. The second objective is to evaluate the impact of the deployment of the prioritised redundant facilities on the network cost and survivability.

1.3 Outline of the Thesis

The rest of the thesis is organized as follows: Chapter 2 presents the literature on the scenario of the world broadband and wireless ecosystem. The characteristics of the optical and wireless communication system and broadband access network are reviewed. Approaches to improve the performance of wireless mesh and the issues related to the propagation loss for wireless network are included. Chapter 3 introduces the HOWBAN architecture and typical network failures. Strategies to model and solve HOWBAN optimisation problems are discussed before presenting some related works in optimising the network for survivability. Chapter 4 examines the FMEA tools used to identify and prioritise redundant network component for HOWBAN survivability. A section to dwell on the determination of the rating for severity, occurrence and detection is included. The results of the finding are analysed and deliberated here. In Chapter 5, the impact of backup power in optimising deployment cost of Hybrid Optical Wireless Broadband Access Network (HOWBAN) with survivability is presented. The strategy deployed and problem formulations are discussed. The results of the study are analysed and discussed. Chapter 6 concludes the thesis by summarising the findings and proposing some future works.

CHAPTER 2

OPTICAL AND WIRELESS MESH COMMUNICATIONS

2.1 Broadband and GDP

Agenda 2030 or Sustainable Development Goals (SDG) launched on September 2015 by United Nations (UN) is positioned to establish an inclusive digital world accessible by all. It is an extension of the 15-year Millennium Development Goal (MDG) initiatives, which focus on anti-poverty introduced by United Nations in 2000. Figure 2.1 shows the 17 SDG and 8 MDG (United Nations, 2015a; United Nations, 2015b).

The SDG focused on sustainable development: social, economic and environmental in both developed and developing countries aiming to bring equitable development to people in all nations in the world. Information and communications technologies (ICT) present an excellent opportunity to support the inclusive growth (Philbeck, 2016) through transforming the lives of people and bring about benefits in health, education, economy, transport, energy, environment, gender equality and sustainability (Philbeck, 2017). Measuring the Information Society Report 2016 by ITU (2017) stated "*In 2016, people no longer go online, they are online*". People who are offline are unable to leverage on the ubiquitous, open and content rich Internet to transform the way they live, communicate and do business with the connected world. The ability to connect to Internet benefits not only the individual but also governments, organisations and private sectors.

Figure 2.1: SDG and MDG Goals.

For the SDG targets to be achieved, there is an urgent need to connect 3.9 billion people or more than half the world's population to the Internet. The offline people are predominantly female, elderly, less educated, have lower income and in rural area (Philbeck, 2016). ITU statistics shows that 31% of the offline population is distributed in Least Developed Countries (LDC) as at 2016 (Philbeck, 2017). Least developed countries (LDC) are low-income countries facing critical structural obstacles to economic growth and sustainable development with low levels of human assets. As at 2015, 47 countries are listed by United Nations as LDC consisting of 1 in the Caribbean, 4 in the Pacific, 9 in Asia and 33 in Africa (Unohrlls, 2016) with a total population of 954 million which is equivalent to 13% of the world's population. The population growth in the LDC is higher than that of the world and the population in the LDC is expected to be increase to 20% of the world total by 2050 (United Nations , 2017). Amongst the reasons for being offline are living in remote or difficult to reach areas and not having access to basic infrastructure such as electricity (Philbeck, 2017).

Broadband is a key enabler to hasten the human progress particularly in the urgent need to lessen the inequalities and to provide even progress in development through the spread of ICT and global interconnectedness (Broadband Commission for Sustainable Development, 2016). Reports have consistently reflected the close correlation between national gross domestic product (GDP) and the availability of the broadband services **(**ITU, 2012). One direct impact of broadband on the economy is through the investment in the large scale infrastructure leading to an increase in the economic activities and immediate employment opportunities.

Broadband provides the connectivity and serves as a platform for facilitating innovation in new products and services to reach new economic sectors such as entertainment, education, healthcare, banking services and e-commerce thus opening up more avenues of economic activities (Philbeck, 2016). Broadband connectivity will improve productivity by enabling access to more resources for better ways of working and making informed management decision which can lessen production time and costs thus leading to gross domestic product (GDP) growth.

Broadband access has great potential in allowing those in the remote and under-developed countries to be connected so as to unlock work opportunities and boosting income. It has been reported that a 10% increase in broadband penetration is likely to have a positive impact, and could raise economic growth by between 0.25% to 1.4%. If broadband speed is doubled, GDP may increase, potentially by up to 0.3% (Philbeck, 2016).

International Telecommunication Union/United Nations on Educational, Scientific and Cultural Organization (ITU/UNESCO) Broadband Commission has identified that broadband is an essential enabler to ICT technologies for achieving the 17 SDG (Broadband Commission for Sustainable Development, 2016) and has clear impact on speed of growth of the economy (Philbeck, 2016). ITU/UNESCO initiated the Broadband Commission for Digital Development to ensure the right to communicate by closing the digital divide gap and providing universal access to information. The Commission was renamed Commission for Sustainable Development in 2015 to response to the new global and technological challenges. The attention of the Commission is on international socio-economic policy and poverty reduction in the context of the UN's Sustainable Development Goals (SDG) by 2030. The five targets of the rebranded Commission are making broadband policy universal (Target 1), making broadband affordable (Target 2), connecting homes to broadband (Target 3), getting people online (Target 4) and achieving gender equality in access to broadband by 2020 (Target 5). Some of the steps recommended to maximise access to broadband are introducing and updating existing regulatory policy for broadband, providing appropriate training to stimulate demand and most importantly identifying measures to make broadband more affordable (Broadband Commission for Sustainable Development, 2016). The Commission has set the measures on evaluating the affordability of broadband which is based on the broadband internet service cost for entry level broadband that should be below 5% of the total household income. By 2015, 83 developing countries had reached the Commission's target of offering basic fixed-broadband services at less than 5% of monthly gross national income (GNI) per capita but the target had only been achieved in five of the 47 United Nations (UN) designated Least Developed Countries (LDC). The percentage of the average monthly income for a monthly fixed broadband package costs in the developed, developing and LDC are 1.7%, 31% and 64% respectively. More efforts are needed to close this significant gap in order to achieve the targets set. Providing subsidies to certain areas or specific socio-economic groups and use of policy to reduce the investment costs in terms of tax exemption or reduction and innovative use of technologies may help drive the cost down (Broadband Commission for Sustainable Development, 2016).

The combination of optical fibre communication with abundance bandwidth at the back end with the short set up time and low deployment cost of the wireless counterpart is deemed as a viable solution to accelerate the delivery of broadband services to the offline population particular those 13% in the LDCs. The research work was carried out based on this background to seek a plausible solution to expedite the broadband adoption

2.2 Optical Communication Optimisation and Survivability

2.2.1 Optical Communication System

A fibre optic communication system consists of transmitter, optical channel and a receiver. The transmitter converts the electrical signal at its input to light signal using either laser or Light Emitting Diode (LED). The light wavelength generated is near to the infrared band that is just above the visible range. Both single and multimode optical fibre can be used as the optical channel (Vacca, 2007). The single mode step index fibre typically has a 9 µm core diameter and allows light to be propagated over a longer distance compared to the multimode fibre at the expense of more expensive laser light source and higher installation costs due to the accuracy required for splicing and coupling. The step index and graded index multimode optical fibre have a larger core diameter of around 50 µm. The difference between the step index and graded index fibre is in the arrangement of their reflective index. The reflective index is identical throughout the core of the step index fibre but decreases from the core towards the core-cladding interface in the graded index fibre. The graded index reduces the pulse spreading giving rise to increase in the transmission distance compared to the step index multimode optical fibre. The larger core diameter of the multimode fibre provides more tolerance in accuracy for splicing and coupling thus lowering the installation cost. The deployment cost is further reduced by using less costly LED light source. The flaw is that the distance of communication will be shorter compared to the single mode fibre. While the single mode fibre is indispensable for the long haul optical network, the multimode fibre is particularly suitable for in building network.

Table 2.1: Industry Standards for Optical Fibre.

(a) Single mode Fibre Types

Single mode Fibre Type	**ISO / IEC 11801**	**TIA**	**IEC 60793-2-50**	**ITU-T**
Legacy	OS1	492CAAA	B1.1	G.652.A or B
Low Water Peak	OS2	492CAAB	B1.3	G.652.C or D
Bend-Insensitive			B6_a1 B6_a2 B6_b2 B6 b3	G.657.A1 G.657.A2 G.657.B2 G.657.B3

(b) Multimode Fibre Types

MM Fibre Type	**ISO / IEC 11801**	**TIA**	**IEC 60793-2-50**	**ITU-T**
62.5/125	OM1[(1)]	A1b	492AAAA	---
50/125	OM2[(2)]	A1a.1	492AAAB	G.651.1
50/125	OM3	A1a.2	492AAAC	G.651.1
50/125	OM4	A1a.3	492AAAD	G.651.1

(1) OM1 is typically a 62.5 µm fibre, but can also be a 50 µm fibre.
(2) OM2 is typically a 50 µm fibre, but can also be a 62.5 µm fibre.

The standard bodies for the specification of optical fibres include International Organization for Standardization (ISO), International Electrotechnical Commission (IEC), Telecommunication Industry Association/Electronic Industries Alliance (TIA/EIA) and International Telecommunication Union (ITU). Table 2.1 shows the optical fibre standards developed by the respective standardising bodies while Table 2.2 indicates attenuation characteristics of the optical fibre listed under ISO/IEC 11801 standard (ISO, 2004).

It can be observed from Table 2.2 that the attenuation for multimode fibre (OM1, 2 and 3) is higher than that of the monomode (OS1) fibre.

Table 2.2: Attenuation specifications of Optical Fibre listed under ISO/IEC 11801 standard.

Fibre Type		Wavelength (nm)	Attenuation (dB/km)
Single mode	OS1	1310	1.0
		1550	1.0
Multimode	OM1, OM2, OM3	850	3.5
		1300	1.5

Photo detectors acts as the receiver to convert the light signal back to electrical signal. Two typical photo detectors or optical receivers in optical communication system are positive-intrinsic-negative (PIN) photo diode and avalanche photo diode (APD). A positive-intrinsic-negative (PIN) photodiode requires external electronics to provide the gain while the avalanche photodiode (APD) converts the energy of the photons into free charge carrier thus creating a multiplication and avalanche effect to provide internal gain (Mun et at., 2009). The capability of APD to amplify the power of incoming signal power makes it ideal to quench the demand of high bit-rate receivers for long haul optical fibre communication. (Campbell et al., 2004; Ker et al., 2013).

The characteristics and advantages of optical communication are shown in Table 2.3.

Table 2.3: Characteristics and advantages of optical communication.

CHARACTERISTICS	ADVANTAGES
Low attenuation.	Long repeater spacing or repeaterless networks.
Wide bandwidth.	Large transmission capacity with simultaneous voice, data and video transmission capabilities.
Immunity from electromagnetic interference.	No shielding problems. No crosstalk
Immunity from NEMP (nuclear electromagnetic pulses).	Ideal for high security applications.
Non-conductive.	Transmitter and receiver electrically isolated.
Non-inductive.	No danger of sparks from short circuits. Perfect for use in hostile environments.

2.2.2 Passive Optical Network

Optical access networks can be configured broadly as point-to-point (P2P) and point to multipoint (PMP) networks. In the point to point architecture, each customer premise (CP) is linked directly to the OLT with a dedicated fibre. Consequently, all customers will enjoy the full optical bandwidth but at the expense of exorbitant deployment cost due to the excessive length of dedicated fibre required. In the point to multipoint architecture the OLT is linked to a remote node (RN) with a feeder fibre to be shared by all the customers. Distribution fibres are then deployed to connect the RN to each of the customer's premise. By locating the RN near to the CP, the length of the fibre required will be much reduced compared to that of the P2P configuration. Deploying PMP networks will result in reduction of bandwidth of each customer. This bandwidth reduction is compensated by the drastic cut in the deployment cost due to the sharing of resources in the network. The PMP configuration is thus the preferred configuration for commercial deployments (Chen et al., 2010; Lee et al., 2006).

The optical access network can be classified into Active Optical Network (AON) and Passive Optical Network (PON) (Jaumard and Song, 2015; Lee et al., 2006). The difference between AON and PON is characterised by the RN used in the distribution network. In Active Optical Network, RN is an Ethernet switch, which is an active element that required the support of electrical supply to operate. Passive elements are chosen as RN in PON. The RN in PON can be either a passive optical switch or an arrayed waveguide gratings (AWG) which can function without electrical supply. The use of the Ethernet switch in AON enables it to provide a longer reach than PON. However, PON has a lower deployment cost compared to AON. The low capital expenditures (CAPEX) and operating expenditures (OPEX) in PON are made possible by the use of only passive components in the outside distribution network (ODN) or outside plant. There is no need for additional cost to supply electrical power which is often required for operating and monitoring systems with electronic components as in AON (Effenberger et al., 2007). The CAPEX is further reduced by adopting a shared fibre architecture where the feeder fibre is shared by multiple users (Truong et al., 2014).

PON with AWG as RN is deployed as Wavelength Division Multiplexing passive optical network (WDM-PON). In WDM-PON, the AWG enables customer to share the optical channel using different wavelength in the optical spectrum (Jaumard and Song, 2015). AWG functions both as optical multiplexer and demultiplexer. In the downstream direction (Jaumard and Song, 2015), AWG demultiplexes the multiplexed signal with different optical wavelengths from the OLT via the shared feeder fibre and distributes them to the designated customer via the respective distribution fibre. In the downstream direction, the signals with different wavelength form each of the customer are multiplexed at the AWG for transmission to the OLT via the single feeder fibre. The advantage of this strategy is that each customer can communicate with the OLT at their own time without any issue on synchronising the transmission between the customer and the OLT. The provision of dedicated optical wavelength to each customer enables each customer to enjoy the full optical bandwidth similar to that of the point to point optical network configuration. To implement WDM-PON, the ONU at each customer's premise has to be furnished with a transceiver that has a light source compatible to the assigned optical wavelength. The number of transceivers in WDM-PON is doubled, as equal number of transceivers has to be installed at the OLT. This implies that 2N transceivers are needed to support N customers.

TDM PON can be deployed to reduce the number of transceivers in WDM-PON. In TDM PON, the optical channel is accessible to the customers based on time sharing basis or time division multiplexing (TDM). The signal from the OLT is broadcasted to all the ONU at the customers' premises. Each ONU will select its messages based on specified packet address or the time slot preassigned by the OLT (Jaumard and Song, 2015; Lee et al., 2006). Passive optical splitters are deployed as RN in TDM-PON. In the upstream direction, each ONU at the customers' premises is assigned specific time slot for upstream transmission to the OLT. Each ONU has access to the full optical bandwidth only during the assigned time slot. This implies that if there are N customers in the network, the effective bandwidth available to each customer is limited to 1/N of the full optical bandwidth.

In TDM PON upstream transmission, dynamic bandwidth allocation (DBA) where the transmission time slots are assigned based on the amount of data to be transmitted by the ONU is adopted. The unused time slot in ONU with less data to be transmitted will be allocated to other ONU that required more transmission time in order to improve the transmission efficiency. Passive optical splitters are deployed as RN. The passive optical splitter splits the optical power equally amongst the customers in the network in the downstream direction. For a network with N ONU, each ONU will received 1/N of the optical power from the OLT. In the upstream direction, the passive optical splitter allows 1/N of the optical power from each ONU to be transmitted to the OLT via the feeder fibre. To support N customers in TDM PON, a transceiver will be required at premise of each customer and at the OLT. The transceiver at the OLT is shared by all the customers thus total number of transceivers required is N+1 which is much lower than the 2N receivers required in WDM-PON. Although bandwidth accessible by the customers in WDM-PON is much higher than that of TDM PON, the additional cost needed to supply larger number of transceivers with dedicated wavelengths, renders it less appealing than TDM PON which offers a lower deployment cost compared to WDM-PON. The more cost effective TDM PON coupled with the widespread acceptance of TDM PON standards by both ITU-T Broadband PON (BPON) (ITU-T 2005) and IEEE Ethernet PON (EPON) (IEEE 2015) have contributed to the dominance of TDM PON in commercial optical fibre network deployment (Lee et al., 2006).

The tree topology of a Passive Optical Network (PON) is shown in Figure 2.2 below (Koonen, 2006; Manharbhai et al., 2017; Yan et al., 2010). The downstream transmission from OLT to the clients is configured as a point to multipoint network architecture while it is multipoint to point in the upstream direction from the clients to the OLT.

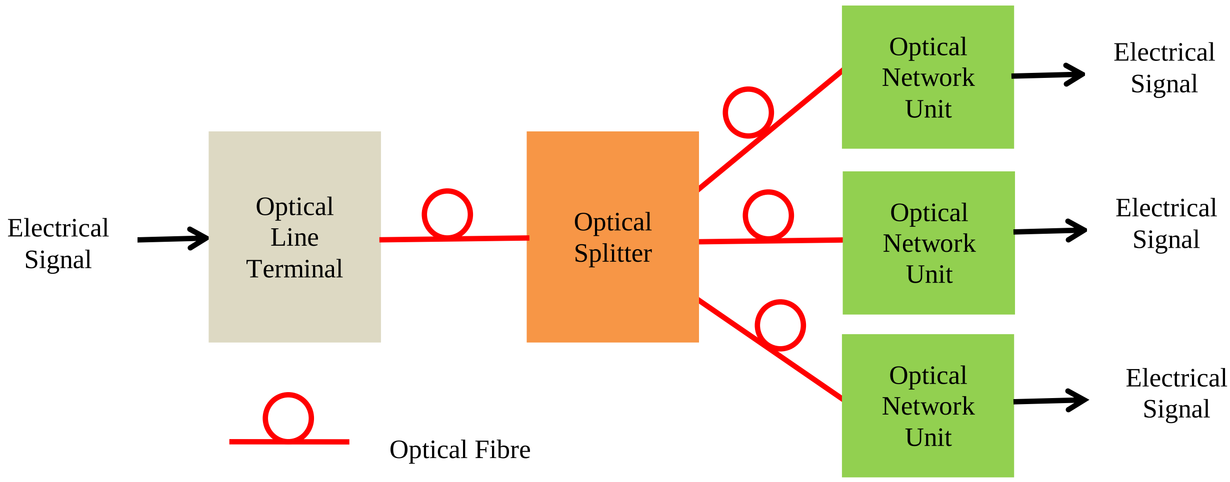


Figure 2.2: Network architecture of a Passive Optical Network (PON).

A PON consists of a central office node, called an optical line terminal (OLT) and an optical distribution network (ODN). The optical distribution network consist of one or more optical network units (ONU) acting as user nodes and optical splitters or Remote Node (RN) which are linked using optical fibres. The fibres between the OLT and the RN is named as feeder fibres (FF) while those between the RN and the ONU are called distribution fibres (DF).

An optical line terminal (OLT) is the endpoint device in a passive optical network (PON) which served to link the devices at the customer's premise (CP) to the Internet via the fibre backbone (Lee et al., 2006). The light sources adopted by the OLT normally consists of laser for long haul network and LED for short haul and in-building network. Typically 1490 nm light spectrum is used for sending signal from the OLT to the ONU or in the downstream direction. The ONU deployed 1310 nm light source when it is transmitting to the OLT or in the upstream direction. Table 2.4 showed the spectrum used for voice, data and video signals (Vaughn et al., 2004).

Table 2.4: Optical spectrum used for voice, data and video signals.

	Downstream	Upstream
Voice and data	1490-nm	1310-nm
Video	1550-nm	

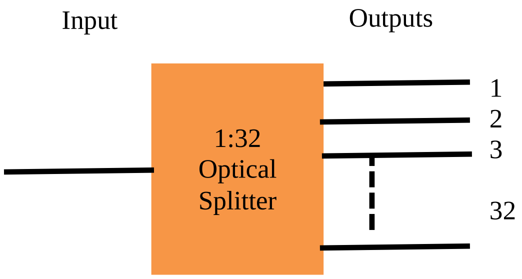
OLT enables the sharing of the fibre by using Time Division Multiplexing (TDM) in the downstream transmission and Time Division Multiple Access (TDMA) is adopted for transmission in the upstream direction (Jaumard and Song, 2015). OLT multiplexes the traffic to all the ONU using TDM into one channel and broadcasts it to all the ONU in the downstream. In the TDM techniques adopted, all ONU will receive the same signal from OLT. The ONU will extract their respective messages during the preassigned time slots (Jaumard and Song, 2015). To make better use of the spectrum in the upstream transmission and to avoid collision due to simultaneous transmission from the ONU in the upstream, TDMA is adopted. In the TDMA strategy, the OLT will allocated time slots for transmission based on specific request from the respective ONU intending to transmit (Garg and Janyani, 2015; Lee et al., 2006).

The single mode optical fibre is used for the long haul while the multimode optical fibre is selected for less critical services. The multimode optical fibre has a larger core size thus lowering the installation costs by reducing the accuracy required for splicing and coupling compared to the single mode optical fibre.

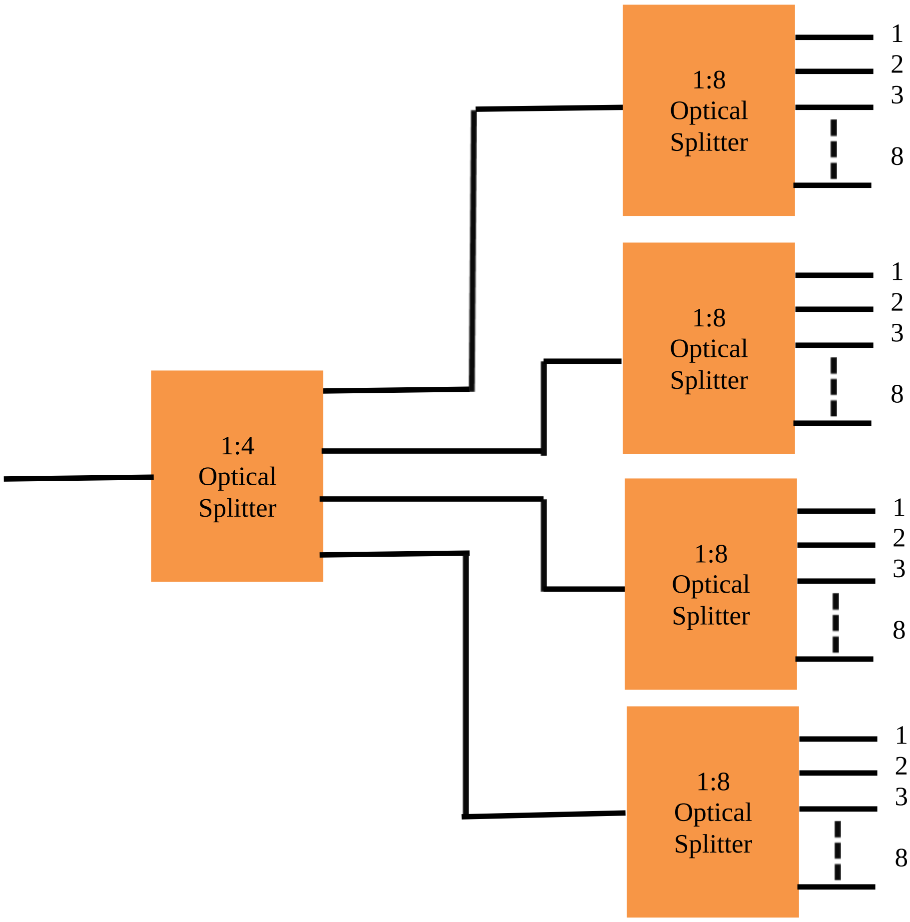
The passive optical splitters is located between the feeder (FF) and distribution (DF) optical fibre. It does not require any power to operate as it has no active electronics (Effenberger et al.,2007). The optical splitter divides the power equally to all its branches (Jaumard and Song, 2015). The 1:N split ratio implied that one incoming fibre input is split into N outputs that can be connected to N ONU. The typical split ratios are 1:4, 1:8, 1:16, 1:32 and 1:64. The optical splitter allows one fibre to feed up to 64 end users for transmission distance of below 5 km (Vaughn et al., 2004). Higher split ratio allow reduction in the cost of feeder cable costs and less complexity in fibre management. However, the bandwidth and power budget for each of the ONU connected to the optical splitter will be reduced proportionately (Ansari and Zhang, 2013). For example each ONU connected to a 1:16 optical splitter in an EPON which can provide 1 Gb/s capacity in both upstream and downstream directions will can obtain an average 60 Mb/s data rate (Li and Shen, 2009). Thus, the split ratio can be used to allocate the bandwidth provided to each ONU user. The insertion loss of the of the passive optical splitter is given by $3.5\log_2 K$ where K is the fanout of the splitter (Garg and Janyani, 2015). The input optical power has to be higher if the fanout is increased in order to maintain the same power at the fanout. Increasing the optical power will lead to higher optic costs at OLT or ONU or both.

The optical splitter can be configured in centralised or cascaded mode (Garg and Janyani, 2015; Vaughn et al., 2004). Figure 2.3 displayed an example for 1:32 split ratio in the centralised and cascaded mode. The cascaded mode will require more PON card compared to centralised mode but has the advantage of reducing the distribution fibre cost.

ONU is typically located at the customer's premise and acts as the bridge between the optical fibre network and the equipment connected in the customers' premises. Its main function is to perform the optoelectronic conversion (Machuca and Kellerer, 2014) which is to convert the light signal to electrical signal in the downstream direction and vice versa in the upstream direction.



(a) Centralised Configuration



(b) Cascaded Configuration

Figure 2.3: Optical Splitter Configurations. (a) Centralised 1:32 split ratio mode; (b) Cascaded 1:32 split ratio mode.

Examples of other generations and standard of PON (Hood and Lu, 2012; IEEE, 2015; ITU-T, 2005; ITU-T, 2012; ITU-T, 2016b) are depicted in Table 2.5.

Table 2.5: PON Standard and Characteristics.

<table>
<tr><td colspan="2">PON</td><td colspan="2">BPON</td><td colspan="2">GPON</td><td colspan="2">EPON</td><td colspan="2">XGPON</td></tr>
<tr><td colspan="2">Full Name</td><td colspan="2">Broadband PON</td><td colspan="2">Gigabit-capable PON</td><td colspan="2">Ethernet PON</td><td colspan="2">10-Gigabit-capable PON</td></tr>
<tr><td colspan="2">Standard</td><td colspan="2">ITU-T G.983</td><td colspan="2">ITU-T G. 984</td><td colspan="2">IEEE802.3ah</td><td colspan="2">ITU-T G.987</td></tr>
<tr><td colspan="2"></td><td>Single Fibre</td><td>Dual fibre</td><td>Single Fibre</td><td>Dual fibre</td><td>100-BASE-BX10</td><td>1000-BASE-BX10</td><td>1000-BASE-PX10</td><td>1000-BASE-PX20</td></tr>
<tr><td rowspan="3">Up-stream</td><td>Wave-length; nm</td><td>1260-1360</td><td>1260-1360</td><td>1260-1360</td><td>1260-1360</td><td>1310</td><td>1310</td><td>1310</td><td>1310</td></tr>
<tr><td>Data Rate; Mbps</td><td>155.52</td><td>155.52</td><td>1244.16 2488.32</td><td>1244.16 2488.32</td><td>100</td><td>1000</td><td>1000</td><td>1000</td></tr>
<tr><td>Distance; km</td><td>20</td><td>20</td><td>20 km (10 km if bit rate >1.25 Mbps)</td><td>20 km (10 km if bit rate >1.25 Mbps)</td><td>10</td><td>10</td><td>10</td><td>20</td></tr>
<tr><td rowspan="3">Down-stream</td><td>Wave-length; nm</td><td>1480-1580</td><td>1260-1360</td><td>1480-1500</td><td>1260-1360</td><td>1550</td><td>1490</td><td>1490</td><td>1490</td></tr>
<tr><td>Data Rate; Mbps</td><td>155.52 / 622.08 / 1244.16</td><td>155.52 / 622.08 / 1244.16</td><td>2488.32</td><td>2488.32</td><td>100</td><td>1000</td><td>1000</td><td>1000</td></tr>
<tr><td>Distance; km</td><td>20</td><td>20</td><td>10 km (bit rate >1.25 Mbps else 20 km</td><td>10 km (bit rate >1.25 Mbps else 20 km</td><td>10</td><td>10</td><td>10</td><td>20</td></tr>
</table>

Newer version of optical access network adopt active devices to increase the reach and bandwidth capacity at the expense of higher deployment cost compared to the TDM PON which has only passive devices at the outside plant. The lower deployment cost associated with TDM PON will be a better candidate for green field deployment in the rural and remote area particularly in the least developed countries. As this thesis is focused on the deployment in rural economy, the newer version of optical access network will not be dealt in detail here.

2.2.2.1 Fibre to the x architecture

The fibre access network may be deployed as FTTH (Fibre to the Home), FTTE (Fibre to the Exchange), FTTC (Fibre to the Curb) and FTTB (Fibre to the Building). FTTE, FTTC and FTTB are typically adopted in area of lower demand for broadband. For area where lower date rate is acceptable, Digital Subscriber Line (DSL) technology can be deployed using legacy copper line to reduce the fibre cost.

In FTTH the fibre is connected directly from the central office to the customers' premises (CP) thus provide the full optical bandwidth to the each customer premise. The downstream and upstream capacity of up to 1 Gbps can be supported. As FTTH requires individual fibre to be connected to each home, the installation costs will be exorbitant compared to other topologies (Amendola and Pupillo, 2008; Farmer and Bourg, 2008; Hutcheson, 2008).

In FTTE, the fibre is terminated at the exchange or central office. To reduce the fibre cost, Digital Subscriber Line 2+ (ADSL2+) technology can be deployed over the legacy copper line to the subscriber's premise. ADSL2+ is able to provide downstream and upstream connection of up to 20 Mbps and 1 Mbps respectively.

In FTTC, the fibre is terminate at a cabinet or pole within a couple of km distance from the customer's premises and signals are forwarded to CP using DSL technologies over copper wires to reduce fibre cost. The link from the street cabinet to the customer's premises can adopt the copper line based Very High Bit Rate Digital Subscriber Line 2 (VDSL2) technology which can upgrade the upstream and downstream connection to 50 Mbps and 100 Mbps respectively but only within a distance 700 m.

In FTTB, the fibre terminate at a building and copper wires can then used to distribute the signals to the premises in the building to cut down the fibre cost. By virtue of the shorter link using the copper line, the VDSL2 technology is able to ramp the downstream and upstream data rate up to 100 Mbps and 40 Mbps within a range of up to 200 m.

2.2.3 Optical Access Network Optimisation

2.2.3.1 Optimisation using splitter ratio

Minimising deployment cost is one of the prime concerns of service providers in rolling out the communication network with the desired quality of service. The desired quality of service of an optical network can be gauged by area of coverage, network capacity in terms of bandwidth, minimum packet delay and packet loss. The deployment cost will have to include the cost of the OLT at the central office and ONU located at the CP together with outside plant which consist optical splitter and the optical fibres that provide the link between the OLT and the ONU (Li and Shen, 2009; Vaughn et al., 2004).

Li and Shen (2009) proposed a strategy to plan a greenfield PON with minimum cost. The authors focused on the splitter ratio and the transmission distance which are aim at reducing the work on trenching and laying of the optical fibre to minimise the installation cost. The split ratio of the optical is determined by clustering the ONU to be served. The ability to select higher split ratio will reduce the transmission distance to the ONU by enabling more sharing of the optical fibre. Consequently less labour in trenching and laying of fibre will be incurred. The approach taken will drastically reduce the capital expenditure (CAPEX) as the cost for land acquisition and the civil works associated with trenching and laying the fibres forms the bulk of the deployment cost (Li and Shen, 2009). The minimisation of deployment cost based on selection and placement of the splitters is also presented in Jaumard and Chowdhury (2012) with the additional constraints of signal power loss associated with the insertion of the splitters. Lakic and Hajduczenia (2007) proposed strategy to maximise the use of existing conduit or copper cable path in order to reduce the exorbitant cost associated in furnishing new paths for the fibre in PON. Either the passive optical splitter and array waveguide granting (AWG) can be selected. The reduction in the deployment cost is realised by maximise the cable sharing by the selection of the type of splitter and the their locations which are determined by the configuration of the ONU cluster formed. The routing of the fibre with minimum obstacles in the path is also selected to shorten the fibre path leading to reduction in the high cost associated with the labour in furnishing new fibre path. The major deployment cost is associated with land acquisition and civil work involved. As the cost of land acquisition and labour varies from one region to another, the actual quantum of the reduction in capex is thus dependent on the geography where the network is deployed.

2.2.3.2 Optimisation using bandwidth allocation

To facilitate fibre path sharing in the downstream transmission, the OLT broadcast the same time division multiplexed (TDM) signals to all the ONU. All the ONU will receive the same signal from the OLT and will extract only the packets contained in the relevant time slots allocated to them. The sharing of the cable in transmitting upstream from the ONU to the OLT is more challenging as the amount of traffic from each ONU are not always the same. Time Division Multiple Access techniques is adopted to address the issue (Kramer et al., 2001, 2002). The selected technique allocated transmission time only to ONU requesting for time slots for transmission. One of the approaches in TDMA is to use equal length for each time slot. This approach is not efficient in using the time slot or spectrum as part of the time slot will be wasted if the traffic from the ONU is not sufficient to fully utilise the allocated time slots. This will create unnecessary queuing time and delay in transmitting the packet for other ONU. Excessing delay will result in buffer overflow. The consequence of buffer overflow is that the packet will be lost. The issue will be acute for ONU with bursty traffic. Dynamic bandwidth allocation (DBA) is predominately used to address the quality of service (QoS) in terms of packet delay and packet loss. The strategy adopted by Kim, et al. (2005) and Kramer et al. (2002) will be discussed here.

An EPON network is assumed in Kramer et al. (2002). The ONU extracted their traffic based on the address indicated in the media access control (MAC) contained in the packets received from the OLT in the downstream direction. In the upstream direction OLT allocates the time slots to each ONU based on the information kept in its polling table which contain the size of the data and the round trip transmission time of each ONU in the network using the Grant and Request command. The Request command is used by the ONU to inform the OLT the size of the packet it wished to transmit. The ONU can begin transmission upon receiving the Grant command which will indicate the transmission duration allotted by the OLT. Following is the description of the transmission process for the scenario of the network with three ONU. The first ONU listed in the polling table can transmit when it receives the Grant command which indicate the transmission time allotted by the OLT. At the end of the transmission time slot, the first ONU will send a Request command to indicate the size of the next block of data to be transmitted. This request will be updated in the polling table of the OLT. Since the OLT is aware of the round trip transmission time for the first ONU, it is able to send a Grant command which will arrived at the second ONU immediately after the first ONU has completed the transmission. Upon completing the transmission of its data, the second ONU will send a Request command to the OLT to indicate the size of its next block of data to be transmitted. This information will again be updated in the polling table of the OLT. The third ONU listed in the polling table will receive the Grant command from the OLT immediately after the second ONU has completed transmission. Just like the second ONU which can transmit immediately after the first ONU ends it transmission, the third ONU will transmit immediately after the second ONU has completed its transmission. At the end of the transmission, the third ONU will send a Request command to request for time slot to send its next block of data. The cycle is then repeated for the first ONU to transmit. The strategy to adopted is simple and by dynamically allotting different transmission duration to the ONU depending on the data to be transmit the transmission enable the cycle time to be fully utilised.

By scheduling the Grants one cycle earlier, overlapping or collision of data from the ONU can be avoided. A guard time is incorporated at the end of an ONU transmission before the subsequent ONU begin to transmit. As the distances between the OLT and each ONU may be different, the receiver at the OLT will need the guard time to readjust the power level and synchronising the clock to the new data from subsequent ONU.

To avoid an ONU with large amount of data to be transmitted from monopolising the bandwidth, the OLT will set a maximum limit on the transmission window for each ONU. An ONU will have to wait for the next cycle to transmit if it is unable to transmit all its data within the transmission window limit.

The bandwidth utilisation for this strategy is effective for uniform traffic condition. If the traffic is not uniform, the performance will deteriorate as presented in Son, et al. (2004). The example given in Son, et al. (2004) assumed that G_{MAX} is the maximum time slot that can be allotted in each cycle. Assuming there is only one ONU is transmitting in a network, the bandwidth utilisation will be limited to $G_{MAX}/(G_{MAX} + NT_g)$ where N is the number of ONU and T_g is the guard time which include the time required to send the Request command. The maximum distance between the OLT and ONU in an EPON is 20 km (IEEE, 2015; Son, et al., 2004) implying a round trip return time of up to 200 µs. It is thus reasonable to select G_{MAX}=125 µs, T_g=5.512 µs which include 0.512 µs for sending the Request command. For N=16, the maximum bandwidth utilisation can be shown to be only 58.6% using the parameters selected. If a larger guard time is selected the percentage will drop further because the scheme does not allot bigger transmission window to the ONU even other ONU are not transmitting.

To improve the bandwidth utilisation factor, Kim, et al. (2005) proposed a sliding cycle time base dynamic bandwidth allocation (DBA). The available cycle time is grouped into guaranteed time (C_i) and shared time. The total guaranteed time (T_G) is dependent on the sum of the guaranteed time allotted to each ONU i.e. $T_G = \sum_{i=0}^{N-1} C_i$ where N is the number of ONU in the network. The shared time (T_S) available is thus given by $T_S = T_{MAX} - T_G - NT_g$ where T_{MAX} is the maximum cycle time to poll all the ONU and T_g is the guard time. If the time slot (R_i) requested by ONU_i is less than (C_i), the OLT will allot to ONU_i a time slot $G_i = R_i$. In case the time slot (R_i) requested by ONU_i is more than (C_i), the OLT may increase G_i to match the requested time slot by ONU_i provided there is unused or remnant time slots $T_{R,i}$ from all the precedent ONU. This strategy in using the remnant time slots from all the precedent ONU is able to minimise the wasted time slots and make better use of the available bandwidth.

2.2.4 Optical Access Network Survivability

2.2.4.1 Network Failures

Various parts of a PON including outside plant can fail due to mechanical, optical or electrical faults (Hajduczenia, et al., 2012). Any failure in the feeder and distribution fibre will present a major impact to the performance of the optical network. Many strategies has thus been proposed to prevent fibre cut in order to ensure the survivability of the optical network.

2.2.4.2 Survivability Strategy

Fibre cut protection generally required the use of an alternative fibre path. The alternative path can be either a redundant fibre or a neighbouring fibre with spare capacity or running on a different laser wavelength (Chen et al., 2008; Chowdhury et al., 2008; Ghazisaidi et al., 2009; Son et al., 2005).

ITU-T recommended four protection architectures to improve the reliability of TDM PON. The four architectures are named as Type A, B, C and D (ITU-T, 2005; ITU-T, 2016a). In Type A architecture, the network is recommended to put in backup feeder fibre. The traffic from a cut primary feeder fibre will be switch over backup fibre. A 1:N optical splitter is required to couple the traffic from either the primary or backup feeder fibre to the distribution fibres. In Type B protection architecture, a cold standby OLT and redundant feeder fibre are provided to the network. The working OLT is connected to the primary feeder fibre and the cold standby OLT is connected to the redundant fibre. As the two feeder fibre are connected to the optical splitter, a 2:N optical splitter is thus required to couple the traffic from the two feeder fibres to the distribution fibres. When the primary OLT failed to function, the cold standby OLT will be turned to ensure that the network operation is not disrupted. Full duplication of all elements in PON is recommended in Type C protection architecture. The duplicated sets of elements are connected in parallel. Each of the feeder fibre is connected to a 1:N optical splitter. The 1+1 redundancy scheme recommended in Type C protection implies that both primary and backup OLT are in operation mode. This feature shortened the time required to switch from the primary to the standby OLT to within 50 ms (Koonen, 2006). In Type D architecture, full protection is achieved by independent duplication of feeder and distribution fibres. A 2:N optical splitter is used to couple the traffic from the feeder fibre to the primary distribution fibre. A 2:N optical splitter is similarly connected between the feeder fibres and the redundant distribution fibres. The traffic from the primary feeder which is connected to the primary OLT may be transmitted via either the primary or redundant distribution fibre. To facilitate this transmission, a 1:2 optical splitter is used to couple the traffic from the primary feeder fibre to either the primary or redundant optical splitter connected to the respective distribution fibres. The same arrangement is adopted for redundant feeder fibre. Comparison of the redundant components used in the various ITU PON protection scheme is shown in Table 2.6. As can be observed from Table 2.6, Type C protection scheme has the highest survivability as it provides full protection of all components in the network. The full protection is however achieved at the expense of higher capex compared to other protection scheme due to the additional number of redundant components required.

Table 2.6: Comparison of ITU PON Protection Schemes

Type	**A**	**B**	**C**	**D**
Redundant OLT	No	Yes	Yes	Yes
Redundant Feeder Fibre	Yes	Yes	Yes	Yes
Redundant Remote Node	No	No	Yes	Yes
Full Redundant Distribution Fibre	No	No	Yes	No
Partial Redundant Distribution Fibre	No	No	No	Yes

The redundancy strategies recommended by ITU-T though is effective in ensuring the reliability of the network but high CAPEX is indispensable in order to deploy the protection architecture (Chen et al., 2010; Wosinska et al., 2009). It is thus essential to explore alternative protection schemes.

To ensure network survivability, Service Interoperability in Ethernet Passive Optical Networks (SIEPON) specifies both tree and trunk protection scheme (Hajduczenia, et al., 2012). In the tree protection scheme, redundant OLT, fibre path and ONU are provided. The switching time to divert data from failed path to the redundant fibre path is short as both the redundant OLT and ONU are on hot standby mode. In the trunk protection scheme only the

OLT and the fibre path are duplicated. The standby OLT can be on cold or hot standby.

Deploying redundant OLT is prevalent in OLT protection and various proposals have been made to reduce the number of redundant OLT. A 1: N OLT protection scheme by using a redundant OLT and an optical switch is proposed in Tanaka and Horiuchi (2008). Data from any failed OLT will be switched to the spare OLT. This approach reduces the number of redundant OLT but nevertheless still required the use of at least one redundant OLT. It will also be unable to handle multiple OLT failure.

A combined ring star fibre connectivity topology to reduce the number of redundant OLT for protection is proposed in Kanungoe, et al. (2015). In P'ng, et al. (2005), the load from the failed OLT is distributed to other working OLT using optical control unit and optical switch. Although no dedicated redundant OLT is deployed, there is still the inevitable and ineluctable requirement of non-dedicated OLT to protect OLT failure.

A survey done by China Telecommunication as reported in Hajduczenia et al. (2012) shows that 80% of the faults in the outside distribution network are due to mechanical connectors which can be avoided by reducing the use of mechanical connectors and adopting appropriate good practice during installation. Equipment failure are due mainly to circuit components and power supplies.

The survey also indicated 13% of the network failures are due to configuration error created by the users and 26% of the failures is at the management platform. These problems can be solved using software define networking which aims to simplify network management and configuration through isolation of management of the control logic and networking devices that forward the traffic in the network (Kreutz, et al., 2015; Nunes, et al., 2014).

While the network operator has full control over the design and quality of network equipment and configuration, the quality of the power supply is typically under the purview of the electricity utility company. It is thus pertinent for the communication network operator to study the impact of the reliability of the electricity supply in order to preserve the survivability of the network. This is part of the research work carried out and will be deliberated further in Chapter 4.

2.3 Wireless Mesh Network (WMN) Optimisation and Survivability

2.3.1 Wireless Communication System

Wireless communication can be deployed using either licensed or unlicensed band. Unlike wired networks, transmission paths of the wireless networks are subjected to the dynamic and unpredictable changes in the characteristics of the wireless medium or propagation path and traffic load (Hari, 2011).

2.3.1.1 Wi-Fi Technology

The licensed band is regulated by the respective economy and required relatively high premium for the usage. The exclusive right given to the license holder to use the spectrum without concerned on interference or spectrum crowding compensates the high premium required to own the spectrum for a specific duration. The regulator provides legal protection and enforcement to prevent interfering transmission from other operators. The absence of interference from operators thus enables the licensed holder to transmit using higher power thus improving the transmission range, signal to noise ratio and the data rate. The transmission range is in terms of km instead of hundreds of meter for the unlicensed band. Cellular wireless communication operators typically used the 900 MHz, 1800 MHz and 2100 MHz licensed band to deploy their services.

A mobile device with Wi-Fi capability can gain access to the Internet via a Wi-Fi router or access point, which is connected to the Internet. It is ubiquitous to deploy Wi-Fi technology for internet access using either the 2.4 GHz or 5 GHz unlicensed band. The 2.4 GHz Industrial, Scientific and Medical unlicensed band offers between 11 to 14 channels depending on the economies. Each channel in the 2.4 GHz band has a fixed bandwidth of 20 MHz. Federal Communications Commission (FCC), USA allocates 24 channels, each with a 20 MHz bandwidth, in the 5 GHz Unlicensed National Information Infrastructure (UNII) band (Chieochan et al., 2010; Ho et al., 2017).

The Wi-Fi technology is based on the IEEE 802.11 standard. The common Wi-Fi standard are IEEE 802.11 a/b/g and n. The 'b' and 'g' standard operates on 2.4 GHz, the 'a' standard operates in the 5 GHz and the 'n' standard may operate in both 2.4 and 5 GHz spectrum. The higher frequency spectrum allows more channels to be allocated and higher data rate to be accommodated at the expense of shorter transmission range. The availability of more channels will enable more data terminals to transmit simultaneously. In the b/g/n using the 2.4 GHz band there are three non-overlapping channels (channel 1, 6 and 11) available for transmission (Chieochan et al., 2010). IEEE 802.11a in the 5 GHz band offers 8 non-overlapping channels (Zubow and Sombrutzki, 2012). There are up to 24 non-overlapping channels in the 5 GHz band. The number of non-overlapping channels allocated varies between different parts of the world. In IEEE802.11 n and ac standard, the number of non-overlapping channel is typically determined by the channel bandwidth selected. For the 20 MHz channel, 21 non-overlapping channels are available. The number of non-overlapping channel is reduced to nine if 40 MHz channels are selected (Ho et al., 2017; INTEL, 2017a).

The recently launched IEEE 802.11ac is only available at the 5 GHz band. The maximum theoretical data rate is 11 Mbps, 54 Mbps, 450 Mbps and 1.73 Gbps for IEEE 802.11 b, a/g, n and ac respectively (Andrews et al., 2007; INTEL, 2017b; Hiertz et al., 2010). The actual data rate for IEEE 802.11n and 802.11 ac depends on the number of antenna and the channels bonded (Ho et al., 2017; INTEL, 2017a).

As the IEEE 802.11 standard and the allocated spectrum is accepted worldwide, the economy of scale has kept the price of the device relatively low compared to those used in the licensed band. This is one of the major factors that result in the prevalent use of Wi-Fi technology, despite the disadvantages of lower transmission power and potential interference from other devices using the same unlicensed spectrum.

2.3.1.2 Link Loss Model

Whilst the traffic load changes can be managed by the network management entities, the dynamic atmospheric changes and environment pose constant challenges to overcome (Hari, 2011). The atmospheric changes will result in variations in line of sight (LOS) path loss between a transmitter and a mobile device. The line of sight path is the direct path between a transmitter and a mobile device. Presence of reflecting objects such as tress and buildings in the transmission environment will result in signals reaching the mobile device via non-line of sight paths. These multiple non line of sight signals are called multipath signals. The mobile device will thus receive multiple signal components due to the multipath propagation environment which is a fundamental aspect in wireless communication. Each signal component arriving at the mobile derive are characterised by attenuation and delay. The paths taken by the transmitted signal to reach the mobile device will determine the extent of the attenuation or reduction in amplitude and delay or change in phase. The received signal is a result of the superposition of the multiple signals received. The actual strength of the signal received by the mobile device will depend on the phase of the multipath signals with respect to that from the line of sight path, which can lead to constructive and destructive interference. The interference will be constructive if the multipath signals are in phase with that of line of sight signal to enhance the signal amplitude received by the mobile devices. The opposite will occur if the signals are not in phase resulting in the attenuation of the LOS signal amplitude. The variation of the resultant signals received due to multipath signals thus lead to the multipath fading phenomenon.

In wireless communication environment with limited mobility, the establishment of a link between the mobile device and the wireless access points/routers is predominantly determine by the path loss of the link.

For wireless broadband systems, the study of wave propagation through the channel is an important task when developing a communication scheme. Therefore, an accurate modelling of the channel is necessary for the design of a broadband wireless scheme (Rahman, 2009). The link loss models commonly used for determining the feasibility of connecting a radio receiver to a transmitter is discussed next.

The communication range of a radio is determined by Effective Isotropic Radiated Power (EIRP) and the transmission path loss. As the transmission power of radio technology including Wi-Fi is regulated by the respective national regulators, the path loss becomes the major factor that determines the communication range. The EIRP for the 2.4 GHz band Wi-Fi transmission is typically set at 500 mW while that for the 5 GHz band is set at 1 W (MCMC, 2013).

There are three models for determining the path loss namely empirical, deterministic and stochastic model. These models are described in detail in Abhayawardhana et al. (2005). The empirical model is based on observations and measurements alone. Stanford University Interim (SUI) channel model (Hari et al., 2003; ITU-R, 2013), Okumura Hata model (Hata, 1980) and the COST-231 Hata model (COST Action 231, 1999) are typical examples of empirical model. These models are frequently applied for predicting the pass loss related to mobile wireless channels. In the stochastic model, a series of random variables are used to model the environment to predict the path loss while the deterministic approach model the path loss based on electromagnetic wave propagation theory.

Authors in Abhayawardhana et al. (2005) performed measurements to validate these three models for the 3.5 GHz Fixed Wireless Access channel. The authors reported that the Electronic Communication Committee (ECC)-33 model proposed by the European Conference of Postal and Telecommunications Administrations (CEPT, 2006) is most suitable for modelling link loss in urban areas.

The protocol and physical model for predicting path loss presented by Gupta and Kumar (2000) is widely accepted by researchers in deciding radio path link.

In the protocol model proposed, node j can successfully receive transmission from node i under the condition that the distance between the nodes is less than or equal to the transmission range; r, specified by the protocol selected (Gupta and Kumar, 2000). The condition is represented by equation (2.1).

$$\left|X_i - X_j\right| \leq r \tag{2.1}$$

where $X_i - X_j$ is the distance between node i and j

r is the transmission range

If there is a node k transmitting using the same channel as node i, co-channel interference can be avoided provided the separation distance of node k and j is

$$\left|X_k - X_j\right| \geq (1 + \Delta)\left|X_i - X_j\right| \tag{2.2}$$

For value of Δ >0, node k will be located out of the communication range of nodes i and j thus eliminating the possibility of co-channel interference (Gupta and Kumar, 2000).

In the physical model proposed by Gupta and Kumar (2000), all nodes choose a common power level for all their transmissions. The physical model is derived as below.

Let $\{X_k; k \in \Gamma\}$ be the subset of nodes simultaneously transmitting at some time instant over a certain subchannel.

Let P_k be the power level chosen by node X_k for $k \in \Gamma$

A transmission from a node X_i, $i \in \Gamma$, is successfully received by a node X_j if

$$\frac{Signal\ Received}{Noise + Channel\ Interference} \geq \beta \tag{2.3}$$

Equation (2.3) can be represented mathematically as:

$$\frac{P_i / \left|X_i - X_j\right|^{\alpha}}{N + \sum_{\substack{k \in \Gamma \\ k \neq i}} P_k / \left|X_k - X_j\right|^{\alpha}} \geq \beta \tag{2.4}$$

where $X_i - X_j$ is the distance between node *i* and *j*, $X_k - X_j$ is the distance between node *k* and *j* and α is the path loss exponent.

Equation (2.4) models a situation where a minimum signal-to-interference ratio (SINR) of β is necessary for successful receptions, the ambient noise power level is $\boldsymbol{N}$, and signal power decays with distance $r\ as\ \frac{1}{r^{\alpha}}$. The path loss exponents; α, for various environments are given in Rappaport (2002). For free space loss (FSL) α is equal to 2 while that for an urban environment is 4 (Rappaport, 2002).

A wireless mesh network can be represented as a graph $G(V,E)$ where V is a set of vertices or nodes and E is a set of edges (Ramamurthi et al., 2008; Stuedi and Alonso, 2006; Tang and Brandt, 2014). In a wireless mesh network, the nodes and the edges respectively model the wireless routers and the link paths. The link criterion is decided using a SNR threshold in a physical model. In the physical model adopted by the authors, an RF logical link is represented by an additional parameter i.e. the link rate R_{ij}^{RF} apart from the transmit power P_i, and the distance between the transmitter i and the receiver j that were used in Gupta and Kumar (2000).

In Tang and Brandt (2014), a link l_{ij}^{RF} is considered feasible if the signal-to-noise ratio (SNR) at the receiver satisfies

$$G_{ij}P_i / N_o R_{ij}^{RF} \geq \phi\ (R_{ij}^{RF}) \tag{2.5}$$

Equation (2.5) indicates that for a transmission rate of R_{ij}^{RF}, the minimum SNR is determined by the function $\phi\ (R_{ij}^{RF})$. Equal noise power spectral density is assumed for all the receivers at the nodes and is denoted as N_o.

G_{ij} in Equation (2.5) represents the gain for the radio channel between node i and node j. The channel gain is determined by the distance between nodes (d_{ij}), far-field (Fraunhofer region) reference distance (d_o) and the path loss exponent, α. Equation (2.6) depicts the relationship.

$$G_{ij} = (d_{ij} / d_o)^{-\alpha} \tag{2.6}$$

In Ramamurthi et al., (2008) the SNR is used to determined the minimum distance where link between node *i* and node *j* can be established as in Gupta and Kumar (2000). Two nodes *i* and *j* can establish a successfully link if the Signal-to-Noise Ratio (SNR) at the receiver exceeds a set SNR threshold β in the absence of interfering signal.

$$SNR = kP_i G_{ij} / d^{\alpha} N_0 \geq \beta \qquad (2.7)$$

where G_{ij} represents the channel gain between the two nodes and k is a frequency-dependent constant (Rappaport, 2002). Equation (2.7) can be rewritten to show that nodes i and j are linked provided the distance between them does not exceed a critical distance d_{th} :

$$d_{ij} \leq d_{th} = \left(kP_i G_{ij} / \beta N_0\right)^{1/\alpha} \qquad (2.8)$$

The Protocol Model using 802.11 Wi-Fi standard that specified maximum transmission power allowed for each of the version is adopted in this research work. The transmission power specified thus limit the possible communication ranges associated with each of the version. The data rate and range of transmission is typically inversely proportional (Heegard, 2001). This research work also adopt the constraints used in Tang and Brandt (2014) where the co-channel interference is not taking into account. In this research work, co-channel interference is deemed to be mitigated by using multiple radios in the wireless routers (WR) and wireless gateways/gateway routers

(GW) with appropriate channel assignment and no nodes are to transmit and receive simultaneously.

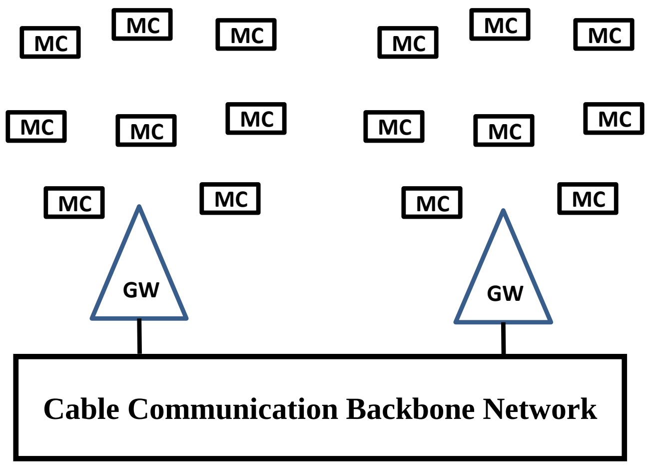
2.3.2 Wireless Mesh Network Architecture

To enhance the resilience of a wireless network, a mesh topology can be deployed. Two architectures are adopted in wireless mesh network; namely ad-hoc and infrastructure architecture as shown in Figure 2.4 (a) and (b) respectively.

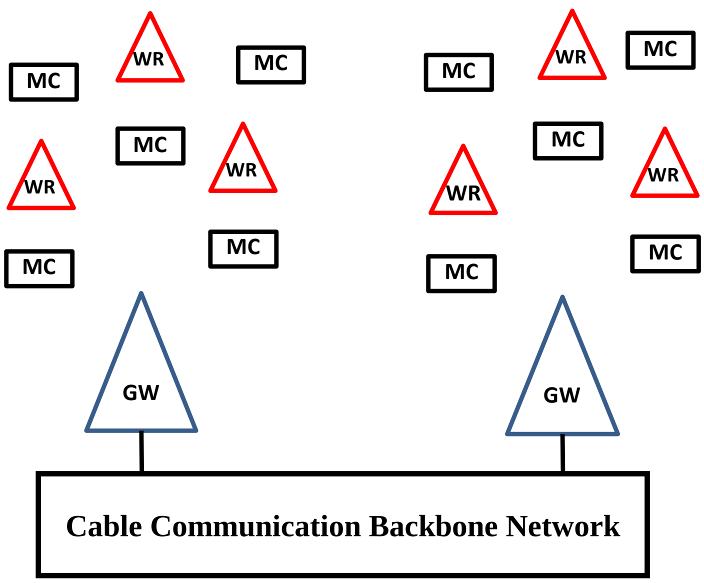
The communication range of a wireless mesh network can easily be extended and it has the capability for self-healing. The characteristic multihop feature allows the range of communication to be extended. In case of node failure, this feature is able to re-route traffic to other nodes thus enhancing the resilience of the network.

2.3.2.1 Ad-hoc Wireless Mesh Network

The ad-hoc wireless mesh network architecture shown in Figure 2.4(a) has a flat topology where all the mobile devices (MC) in the network can form part of the transmission path or nodes together with the gateway routers (GW) even without the access points (WR). This feature implies that each node



(a)



(b)

FIGURE 2.4: Wireless Mesh Network Architectures.
(a) Ad-hoc WMN; (b) Infrastructure based WMN
MC: Mobile Clients WR: Wireless Router GW: Gateway Router

will be involved in forwarding packets from other nodes. The additional load will result in the reduction in the throughput of each node due to the limited channel capacity available to it (Li et al., 2001). Since there is no fixed routers in ad-hoc networks, the nodes need to be connected dynamically when there is movement in the nodes (Royer and Toh, 1999). The dynamic nature of the network topology and channel capacity make it less often applied in mobile communication network. Ad-hoc wireless mesh network is however a preferred choice for data acquisition sensor networks where there is very minimum or no mobility (Royer and Toh, 1999).

2.3.2.2 Infrastructure Based Wireless Mesh Network

The infrastructure based topology shown in Fig 2.4(b) is hierarchical in nature. An infrastructure based wireless mesh network has three major sections viz mobile devices, access points and gateways. The mobile devices remote from the gateways can only access the gateways via the access points within their range. The access points enable the remote mobile client devices to connect to the Internet via the gateways. For the infrastructure based wireless mesh network shown in Figure 2.4(b), the mobile clients (MC) will connect to the Internet via a wireless router or access point (WR) within its best communication range. The data received from MC is relayed by the host WR to a gateway router (GW). Since the access points (WR) and gateway routers (GW) in the network are connected in a mesh topology, the range of communication of a WR can easily be extended by allowing their traffic to be relayed or 'hopped' to neighbouring WR. This multi-hop feature enables the communication range of a WR to be extended easily. The self-healing capability is achieved by re-routing traffic to alternative neighbouring WR if the intended link failed.

Gateway routers (GW) are typically sited within communication range of several WR and are tasked to link the WR connected to them to a cable backbone communication network.

As the research is on mobile communication, this discussion here will focus on the infrastructure based wireless mesh network optimisation and survivability.

2.3.3 Wireless Mesh Network Optimisation

Like any wireless communication system, the number of clients that can be served in a wireless mesh network is inundated by spectrum limitation, unpredictable weather conditions, radio interferences and transmission power regulated by the authority. Many innovations have been proposed to extend this limited resource so as to provide services to as many clients as possible. Some innovations that have been proposed to optimise the scarce spectrum resource are presented here. The focus is on strategies and innovations related to radio channel, network topology, routing strategy and channel assignment.

2.3.3.1 Optimisation using radio channel

Single channel radio has been adopted in wireless mesh network to reduce the implementation cost. Consequent to that the numbers of hops, packet delay increases in proportion to the number of wireless mesh network routers deployed (Correia et al., 2009). The delay issue was resolved by introducing multiradio into the network. Multiradio implies that multiple radios are installed at the node. This approach increases the equipment cost but it can provide significant improvement in the network throughput. The availability of cost effective wireless devices has made the multi-radio a standard design. The additional channel in the multi-radio devices double up as a backup channel and is able to resolves the robustness issues faced by single radio network where failure of the radio will result in link disruption.

The benefits of using multi-radio are not directly proportional to the number of radio used. Deploying more than three radios will not provide much improvement in terms of connectivity compared to the use of single radio (Robinson and Knightly, 2007). Similar finding is reported in Benyamina et al. (2011) which also explained that the interference caused by the extra radios will overwhelm the attempts to resolve connectivity or robustness of the network by introducing more radios.

2.3.3.2 Optimisation using network topology

Placing wireless node in hexagonal topology is often deemed to be able to provide the best coverage with minimum cost when comparing to full grid topology. An innovation introduced is the use of triangular topology. Although there is no significant difference in coverage area in deploying triangular topology when comparing to hexagonal topology, Robinson and Knightly (2007) have analysed and shown that a triangular topology tends to fare better than the hexagonal topology in terms of coverage holes and worse case coverage. Coverage holes are defined as a client location with less than 50% probability of connected to a mesh node. When the comparison is done based on the ratio of coverage holes versus node densities per km^2, the improvement factor in terms of coverage hole is marginal. However, triangular topology displayed significant improvement when worse case coverage probabilities are considered. Worse case coverage is based on the worse case client distance to the nearest mesh nodes in each tessellation. The mesh node density per km^2 for the triangular tessellation is about 50% less than that of hexagonal tessellation to achieve the same worse case coverage probability. In Khalifa (2011), it has been shown that the capacity of a network with 2x2 access points in a triangular topology is 25% better than that of square and hexagonal topology. However as the number of access points increases to 10x10, the improvement diminishes to about 2%.

2.3.3.3 Optimisation using routing

Routing is one of the important criteria in optimising the performance of the wireless mesh network and finding the best routing algorithm remained a challenge to the researchers.

In Narlikar (2010), it has been demonstrated that deploying the Even-Odd activation framework which is the wire line scheduling algorithm in wireless network, a delay of only up to twice that of the respective wire line topology can be achieved.

As multihop connections is employed in wireless mesh network to route traffic to the gateway via multiple nodes, inefficient routing of packets will result in uneven distribution of wireless links leading to unacceptable link delays between wireless nodes. Minimum Hop (MHRA) and Shortest Path (SPRA) routing algorithm are the simplest that can be implemented (Sarkar et al., 2008). Both of the algorithm aims at sending the data packets at the fastest possible time. Load balancing is not being considered and consequently congestion may occur in the link of the network. The number of neighbours will become larger as the size of the wireless mesh network is increased thus providing additional alternative paths for the packets. These alternative paths helps improve the robustness of the transmission path against link failure but without proper route selection mechanism, the packets may take more hops to reach its destination at both the upstream and downstream path. Intolerable delay may occur as a result of the extra hops.

In Sarkar et al. (2008), an innovative Delay Aware Routing Algorithm (DARA) based on Link State Prediction (LSP) was designed to compute the expected delay of a route. Packets will only be transmitted if the expected delay computed is below a preset threshold. In LSP, the state of each wireless link is model as a queue and the associated delay is predicted. The weights assigned to the link are proportional to its delay. Based on the weight assigned to each link, K minimum weight of the paths is computed. The K minimum weight paths prevents the path with the minimum delay from being selected by all packets which may lead to link congestion due to multiple rejections which often occurred in MHRA and SPRA especially when the traffic load increases. Although deployment of the algorithm does not show significant difference in the delay compared to MHRA and SPRA for normalised load below 0.4 but as the load increases the advantage of DARA is observed. At a normalised load of 0.95, the improvement of up to 30% was reported.

2.3.3.4 Optimisation using channel assignment

IEEE802.11 b/g standard typically deploy eleven channels from the fourteen channels available for communication. Three of the channels; channel 1, 6 and 11 are orthogonal and non-overlapping (Tang X.J. et al., 2010). The remaining eight channels are partially overlapped. The three non-overlapped channels are commonly used as to avoid adjacent channel interference. When using the three orthogonal channels to cover a large area, frequency of spectrum reuse will be higher and may increase the co-channel interference.

Chances of co-channel interference will be much lower for the partially overlapped channel. Although the partially overlapped channels which have less possibility of suffering from co-channel interference and can offer much bigger spectrum, network capacity and throughput, they are usually avoided as extra effort need to be taken to address the adjacent channel interference. Researchers have proposed several innovations and shown that the challenges to overcome the possible interference related to simultaneous transmission using the overlapped channels can be resolved.

To reduce the interference in a wireless mesh network, different radio channels are assigned to neighbouring nodes so that simultaneous transmission can be performed thus leading to improved network capacity. Interference will not occur if the number of node is less than half the number of radio channel available (Tang X.J. et al., 2010). The interference can be kept to a minimum, by reducing the number of nodes to provide the coverage so that the number of channel required can be lowered. In Tang X.J. et al. (2010), a strategy to reduce the nodes aiming to reduce interference but not jeopardising the network capacity was proposed. The strategy proposed is to reduce the redundant connection between nodes. Logical link weight is also used to decide on channel assignment with the aim to distribute the load equally among the nodes.

In Wang et al. (2011), an innovative strategy; Partially Overlapped Channel Assignment (POCAM), is introduced to improve the assignment of partially overlapped channel in a wireless mesh network. In POCAM, the assignment problem is transformed into to weighted conflict graph. Using the algorithm, each node is then assigned a channel that satisfied specified link weight. Back tracking search algorithm is then used to formulate the POCAM algorithm. The simulation done using the POCAM algorithm showed that irrespective of the network size or node distribution, the throughput of a wireless mesh network using partially overlapped channels assignment scheme outperform that using non-overlapped channel assignment (NOCA) by at least 43%.

Innovations in the deployment of the non-overlapped channels in IEEE802.11 b to improve the network capacity are also discussed in Pollak et al. (2012). Network capacity can be increased by using the proposed First Random Channel Assignment algorithm (FRCA) to reduce the link interference. In FRCA, links using the same radio channel and are within the interference range are assigned channel based on the load expected and the effect of interference. Greedy algorithm and shortest path routing are used to implement the channel assignment. The approach proposed is able to give an improvement of at least double that of Load Aware Channel Assignment (LACA) in terms of throughput and end to end delay when 6 to 12 channels are used. LACA is similar to FRCA except that its channel assignment is fixed while FRCA uses random channel assignment.

The innovation introduced in Hoque et al. (2009) is the use of interference vector matrix to determine channel assignment. The interference vector matrix indicates the impact of adjacent channel interference from neighbouring channels available at the node. The interference factor is computed based on the interfering range and the geographical distance between the nodes. Interfering range is the distance within which transmission from the nodes interfere with each other. Before a channel is assigned to a link, the total interference factor due all the eleven channels at both the nodes of the link is computed. The channel that gives the lowest interference factor and is less than a threshold level of 1 will be assigned to the link. Since it is known that channel with a channel separation of less than 5 will create adjacent interference, the setting the threshold level at 1 will ensure that those channels will be excluded from the assignment. The algorithm was evaluated using both the non-overlapped and overlapped channels. It was shown that the network capacity improves by more than 15% on average when non-overlapped channels are selected. It has been shown that deploying random topology can increase the number of channels that can be assigned and improve the network capacity by more than 15% depending on the load condition, when comparing to the use of non-overlapped channels.

Fu et al. (2008) observed that in a typical wireless mesh network, mobile clients will seek access to internet connection. The connection is done via a local wireless node which relays the data via its neighbouring nodes to an internet gateway which is connected to a wire line backbone. Consequent to that, the nodes near the internet gateway tend to experience heavier traffic compared to the remote local node. A bottleneck may be created if insufficient bandwidth, transmission time slots or radio channels are allocated to the nodes near the internet gateway. In order not to degrade the network capacity, the uneven distribution of traffic flows in the network needs to be resolved.

Fu et al. (2008) resolved the problem by an innovative load balancing technique where channel allocated to nodes with less traffic will be merged so that nodes with heavier load will be allocated more channels. A mechanism is also put in place to trigger the re-assignment of the channel whenever changes occur in the load distribution of the network. The internet gateway monitors the traffic of all the adjacent links. The re-assignment is activated whenever the traffic on a link is below a set threshold.

Based on the findings of Garetto et al. (2006) which showed that non-coordinated interference results in significantly higher transmission losses and unfair capacity distribution amongst the links, as compared to coordinated interference, Naveed and Kanhere (2009) has designed a cluster-based channel assignment scheme (CCAS) that prioritises the minimisation of non-coordinated interference over coordinated interference. The scheme is able to minimise non-coordinated interference without having to know of the exact locations of its neighbours. The classification of the interference link depends on the geographical separation distance between the transmitter and receiver of the stations as shown in Table 2.7.

Table 2.7: Separation distance between transmitter and receiver in Coordinated and Non-Coordinated Interference.

Station	Tx / Rx	Coordinated	Non-Coordinated		
A	Tx	Yes	Yes	Yes	No
	Rx	Yes	No	No	Yes
B	Tx	Yes	Yes	No	Yes
	Rx	Yes	No	Yes	No
Separation Distance		Less than Rtx	More than Rtx	Less than Rtx	Less than Rtx

Tx – Transmitter / Rx – Receiver / Rtx –Transmission Range

Coordinated interference is due to transmitters and receivers of two stations which are within each other's transmission range. Non-coordinated interference can occur if the transmitters of both stations are out of the transmission range but their transmitter and receiver are within each others transmission range as shown in Table 2.7.

In the scheme, the network is first logically partition into clusters which are non-overlapping. To eliminate non-coordinated interference in the cluster, each cluster is assigned a common channel which is orthogonal to that assigned to neighbouring clusters. Non-coordinated interference between inter-cluster links are minimised by assigning channels that create the least interference. This is achieved by allocating unassigned orthogonal channels in the coordinated interference minimisation to intra-cluster links.

The performance of the CCAS was compared to Breadth First Search Channel Assignment (BFS-CA) and Hyacinth channel assignment method. In BFS-CA, the impact of interference is evaluated based on channel utilisation and number of interfering links. In Hyacinth, the traffic load forms the basis for evaluation. The results simulated based on single hop flows indicated that the CCAS performed better than both the benchmark scheme in terms of channel utilisation, network capacity and effectiveness in handling non-coordinated interference. The degradation of the aggregate goodput of end-to-end multi-hop flows for the benchmarked schemes is much higher compared to CCAS.

Innovations in Correia et al. (2009), Khalifa (2011), Narlikar (2010) and Pollak et al. (2012) are able to ensure the network designed will be able to provide the required service based on planned demand. Innovations in Narlikar (2010) and Sarkar et al. (2008) attempt to ensure that traffic load is evenly distributed amongst all the available links so as to avoid deterioration of the SNR of any particular link due to overloading. It should be noted that the innovations proposed does has its tradeoffs between the best load distribution and the potential long delay in transmission when diverting traffic to routes with low traffic loading. Innovations in Fu et al. (2008), Hoque et al. (2009), Naveed and Kanhere (2009), Pollak et al. (2012), X.J. Tang et al. (2010) and Wang et al. (2011) deal with issue of interferences caused mainly by adjacent and co-channel interference.

As each of the innovations discussed above have definite influence on the wireless mesh network, the performance of the network can be gauged more accurately by considering their impacts simultaneously (Li et al., 2008; Li et al., 2009; Mohsenian-Rad and Wong, 2007; Wu et al., 2012; Zhang and Zhang, 2008;). The integrated approached has shown that the performance tends to be better compared to design based on single criteria. In Li et al. (2009) and Wu et al. (2012) radio placement and channel assignment are optimised simultaneously. Cross layer design is studied in Li et al. (2008) and Zhang and Zhang (2008). In Mohsenian-Rad and Wong (2007) the network is planned by taking into consideration all the related aspects.

The approaches used in Li et al. (2008), Li et al. (2009), Mohsenian-Rad and Wong (2007), Wu et al. (2012) and Zhang and Zhang (2008), however do not address fully the dynamic nature of the wireless mesh network. In Ding et al. (2013) and Wang et al. (2009) the dynamic traffic change and channel allocation are included in their study in order to evaluate the performance closer to practical implementation. The availability of new technology such as software defined radio and cognitive radio can facilitate the study of wireless mesh networks that can monitor and vary the network performance dynamically. Dynamic smart frequency management using cognitive radio has been studied in Chowdhury and Akyildiz (2008), Mumey et al. (2012) and J Tang et al. (2010).

More innovations are required to satisfy the continuous demand for more bandwidth to support higher data rate and wider coverage area. Research work in the area of network survivability, security and energy usage together with radio over fibre and wireless optical systems can be enhanced so as to exploit the limited radio frequency spectrum to the fullest.

2.3.4 Wireless Mesh Network Survivability

2.3.4.1 Network Failures

As the research involves mobile communication, this discussion here will be focus on the infrastructure based wireless mesh network. Typical failure in wireless front end can be due to atmospheric attenuation and interference, network congestion or equipment failure (Sterbenz et al., 2002). Severe atmospheric conditions and interference may result in link failures. Excessive link failures which are not addressed in time will lead to network overloading and packet loss. Failure in WR/GW segment will disrupt the link path for data flow resulting in potential changes in network topology for routing and creating network congestion (Waharte et al., 2006). In the worst case, the network survivability may not be maintained.

2.3.4.2 Survivability Strategy

Deployment of redundant components is the ubiquitous practice in improving the reliability and survivability of a network due to node and link failures. Numerous studies have been done to evaluate the impact of node failure and strategies to resolve the problem.

The use of multiple radios provides more radio channel for communication thus enabling higher data capacity and throughput. The extra radios may provide wireless backup link for failure of radio in the main path thus improving the robustness of the network (Correia et al., 2009). This strategy will increase the capital expenditure but it is still viable due to the drop in the cost of radio hardware (Correia et al., 2009). However, studies have shown that employing more than three radios will be counter productive to the attempt to improve connectivity due to the excessive interference created by the additional radios (Benyamina et al., 2011; Robinson and Knightly, 2007).

Deployment more WR nodes inevitably will increase the coverage area and more choices of transmission paths that lead to improve network resiliency while the reduce path loss will improve the network throughput (Narlikar et al., 2010). The drawback is that the hop-count will escalate in proportion to the WR and will incline to make the link delay intolerable (Narlikar et al., 2010; Sarkar et al., 2008). Authors in Kiese et al. (2009), Narlikar et al. (2010) and Sarkar et al. (2008) reported some algorithms such as minimum hop, shortest path, delay aware and least state prediction to optimise the link latency. This approach will increase the complexity of the algorithm which can be reduced by optimising the siting of redundant WR and GW to maximise the number of alternative path to re-route data from failed nodes without creating undue delay.

CHAPTER 3

HYBRID OPTICAL WIRELESS BROADBAND ACCESS NETWORK (HOWBAN)

3.1 HOWBAN Architecture

While wireless network can furnish the required mobility, it is constrained by the scarce favourable radio spectrum. On the other hand, optical fibre network is able to fulfil the vast bandwidth desired but unable to quench the ongoing plea for mobility. Studies have suggested that a hybrid optical and wireless broadband access network (HOWBAN) that incorporates a high speed optical fibre network at the backend and a wireless mesh mobile network at the front end would be primed to provide a compromise to the market pressure (Sarkar et al., 2007a; Zheng et al., 2009). Typically, the optical network will serve as the backhaul of HOWBAN to distribute the gigabit to tens of gigabit of traffic that it is capable of handling. The optical network also aggregates the traffic arising from the wireless network and deliver to the backbone connection. Wireless mesh network with its self-healing characteristics is an obvious choice as the architecture for the wireless communication network at the front end of HOWBAN.

The regulatory permission to operate wireless mesh network in the licensed free 2.4 and 5 GHz band is a positive factor that has spurred the widespread adoption of the 802.11 Wi-Fi technologies in wireless mesh networks. The infrastructure based WMN front end using Wi-Fi technology is preferred for mobile communications is selected for this research work.

Wireless mesh networks are characterised by their short deployment time and relatively low implementation cost compared to cabled network. The HOWBAN with infrastructure based wireless mesh network is shown in Figure 3.1.

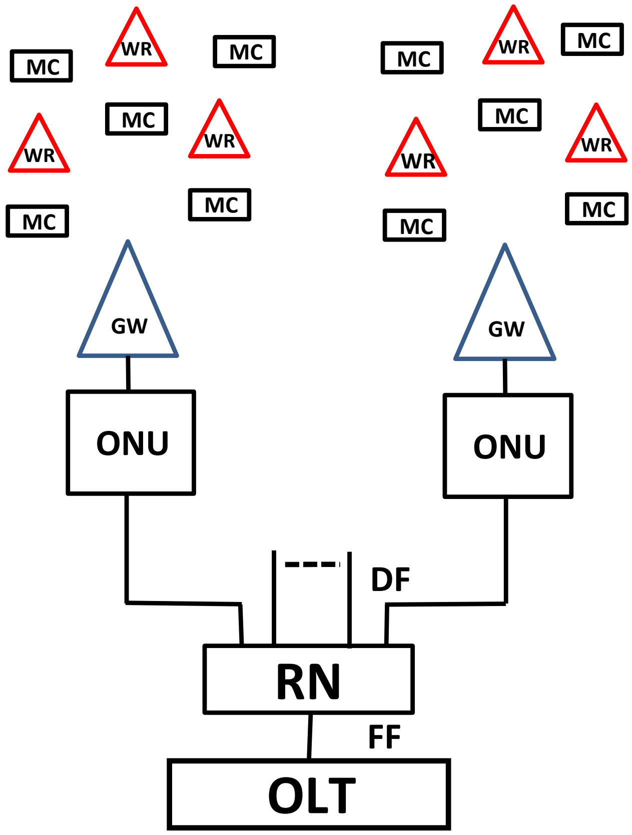


FIGURE 3.1: HOWBAN Architecture with Infrastructure based WMN.
MC: Mobile Clients WR: Wireless Router GW: Gateway Router
ONU: Optical Network Unit
DF: Distribution Fibre RN: Optical Splitter FF: Feeder Fibre
OLT: Optical Line Terminator

Wireless routers (WR) act as access points to serve the mobile clients and are connected to the GW using multihop strategy, which helps in extending the communication range. The multihop feature also enables the traffic from a failed WR to be re-routed to neighboring WR thus fortifying the resilience of the network. Each gateway router (GW) is associated with an Optical Network Unit (ONU) which acts as an interface between the wireless front end network and the optical backhaul network. The Optical Network Unit (ONU) converts the electrical signal received from GW to optical form in the upstream direction. Data from the ONU continued its path as optical signal using the distribution fibre (DF) to the optical splitter or remote node (RN). The passive optical splitter acts as a power combiner to assemble the upstream data from various ONU and forward it via the feeder fibre (FF) to the Optical Line Terminal (OLT) which is conventionally sited at the central office (CO). The data received by the OLT is presented to the Internet via the terrestrial cabled network.

On the reverse or downstream path, data from the Internet will be returned to the source GW via the FF, Optical splitter, DF and ONU using Time Division Multiplexing (TDM). The OLT, feeder fibre, optical splitter, distribution fibre and the ONU form a passive optical network (PON). The optical splitter serves to divide the optical signal power from the feeder fibre into multiple and equal but lower power signals to the distribution fibres. Each distribution fibre is terminated with an ONU which converts the optical signal to the electrical signal and fed to the GW associated with it.

In TDM-PON duplex communication where upstream and downstream signals can be transmitted simultaneously over the same fibre is achieved typically by using 1490 nm light wave laser signal in the downstream from OLT to ONU and 1310 nm light wave in the upstream from the ONU to the OLT. In WDM-PON, duplex communication is achieved by deploying multiple laser wavelengths for the upstream and downstream paths.

Minimising the network deployment cost is essential for successful acceptance of HOWBAN (Filippini, and Cesana, 2010) however the ability to ensure that the network can continue to function during failure is equally important (Ghazisaidi et al., 2009). The introduction of high bandwidth technology such as Next Generation Passive Optical Network (NGPON), Long Term Evolution – Advanced (LTE-A) and Fifth Generation (5G) cellular network with 10 times higher bandwidth and in particular IEEE802.11ac Wi-Fi standard will increase the number of clients that can be served by the nodes in HOWBAN. The failure of the network component will affect more mobile clients (MC) compared to the previous technology. Reliability and survivability of HOWBAN is thus becoming more critical and urgent.

Authors in Lee et al. (2011) have shown that increasing the number of potential sites for wireless access points (WR) has little impact on the deployment cost which is dominated by trenching cost. The simulated result obtained indicated that full survivability cannot be assured by merely optimising the cost of a Wireless Mesh Network (WMN). Node failures in the WMN need to be addressed in order to improve network survivability. In view of the growing trend in network data rate and adoption of mobile communication services, unrecovered node failure will affect significantly both network operators and users. The network operators have to guarantee that the level of connection availability is adhered to the Service Level Agreement (SLA) (MCMC, 1998) as required by the respective national telecommunication regulator (ITU-T, 2016a) and retain client loyalty so as to maintain and improve their ARPU (Average Revenue per User). For the users, particularly those in industries relying on ICT services for mobile financial transactions, network failure will create loss in revenue (BOG, 2015; Hirose et al., 2010).

Typical network failures and various works that have been attempted to minimise cost of network redundancy in order to preserve survivability of HOWBAN will be presented in next section.

3.2 Network Failures

The 1:1 redundant network offers the simplest and most effective solution as insurance to network survivability as it can drastically reduce the recovery and down time but will attract exorbitant cost and is not economical (Wosinska and Chen, 2008). As redundancy cannot be averted to maintain network survivability, various attempts have been done to reduce network component redundancy. This section will review the work that has been done to resolve the failure in the backhaul and front end of HOWBAN.

3.2.1 Backhaul Failures and Mitigation Strategies

Most of the investigations on optical network node failures are done on the impact of equipment failure and fibre cut as discussed in Section 2.2.4. The objectives revolve around protection strategies and minimising the physical redundant system to ensure network can continue to operate by providing an alternative or multiple paths for data from the failed node or fibre break. As previously mentioned provision of an alternative fibre path is often used to mitigate fibre cut failures. The alternative path can be realised by deploying a redundant fibre or capitalising on neighbouring fibres with spare capacity or running on a different laser wavelength (Chen et al., 2008; Chowdhury et al., 2008; Ghazisaidi et al., 2009; Son et al., 2005). The availability of a wireless front end in HOWBAN provides additional strategies for mitigating the backhaul failures.

In HOWBAN, techniques to ensure reliability of the optical backhaul include the diversion of traffic of ONU attached to failed distribution fibre to neighbouring ONU (Kantarci and Mouftah, 2010; Liu et al., 2012; Sarkar et al., 2007a).

In Sarkar, et al. (2007b), the distribution fibre cut protection is achieved wirelessly by routing traffic from GW with broken optical path to neighbouring GW with spare capacity and attached to working optical path. The proposed scheme can avoid the use of redundant fibre assuming an alternative gateway router (GW) with sufficient spare capacity is available but this approach will complicate the design of the wireless mesh network.

In Feng and Ruan (2011) each parcel of the hybrid network consists of an OLT and a RN servicing several ONU. Each ONU is attached to a GW linked to their respective WR. A backup ONU is assigned to each parcel which is connected to its peer in at least another parcel via an optical fibre. When discontinuity due to failure in either DF, RN, FF or OLT in a parcel occurred, data from this parcel will be routed using the backup ONU to its peers in other parcel. The backup ONU in the new parcel will then distribute the data received wirelessly to all GW which are connected to live ONU and OLT. In this case, survivability is achieved using the backup ONU and a redundant fibre connected to neighbouring backup ONU.

Optical switches are used to divert the data to redundant fibre when traffic flow is blocked due to failure in optical path or ONU (Ghazisaidi et al., 2009; Wong, 2014)

3.2.2 Front End Failures and Mitigation Strategies

The network failure and mitigation strategies for wireless mesh network presented in Section 2.3.4 are equally relevant in HOWBAN and are restated here. Atmospheric attenuation and interference, network congestion or equipment failure are typical causes of failure in the front end of HOWBAN. Network topology for routing may be altered due to failures in

WR/GW segment. This will result in the disruption of the route for data flow and network congestion which may lead to failure in network survivability. The trend in the reduction of the cost of radio hardware (Correia et al., 2009) has make the option of using multiple radios more viable. The increase the radio channels can facilitate higher data capacity and throughput apart from improving the robustness of the network. It has been found that there is no advantage in employing more than 3 radios to improve the network connectivity due to the excessive interference created by the additional radios (Benyamina et al., 2011; Robinson and Knightly, 2007).

While deploying more WR nodes can extend the coverage area and improve network resiliency, the additional nodes may result in excessive hop count which may result in unacceptable link delay (Narlikar et al., 2010; Sarkar et al., 2008). Algorithms such as minimum hop, shortest path, delay aware and least state prediction are used to optimise the link latency but at the expense of increase in the complexity of the algorithms (Kiese et al., 2009; Narlikar et al., 2010; Sarkar et al., 2008). Excessive delay can be reduced by optimising the siting of redundant WR and GW in order to maximise the number of alternative path to re-route data from failed nodes.

3.3 Modelling and Solving HOWBAN Optimisation Problem

3.3.1 Modelling and Simulation

Cost, availability and reliability are the major concerns of telecommunication services. Network architecture will determine the hardware layout and thus directly affecting the capital investment required. The number of clients and thus average revenue per user (ARPU) is not only dependent on the coverage provided by the radio equipment in the network. ARPU also depends on the available radio channels, which is dependent on the allocated radio spectrum. Efficient and innovative channel routing and assignment of the radio channel can increase access to higher number of clients without increasing the spectrum requirement. Planning the network architecture and the channel assignment will enhance not only the availability of the network but also its reliability. Optimisation of the hybrid optical and wireless mesh communication network is thus an essential tool required to implement a network will minimum cost and provide channels to maximise the number of subscribers. Optimisation is the process to find the best design (Parkinson et al., 2013) and a good model is necessary for the optimisation to be completed quickly. Appropriate modelling and optimisation tools have the capability to predict the reliability of the network more effectively.

Modelling and simulation are two major steps in studying the optimisation of HOWBAN. Modelling attempts to produce a model that can be used to evaluate the impact of the changes on the desired outcomes of a system or network. Simulation typically employ a computer based tool to assess or optimise the performance of a system or network under varied constraints and scenarios (Carson and John, 2004; Maria, 1997). The selection and use of appropriate modelling and optimisation tools or solvers have the capability to predict the reliability of the network more effectively.

3.3.2 Modelling HOWBAN Optimisation Problem

Modelling tools are required to solve complicated problems such as resource allocations issues in manufacturing and telecommunication industries. Those problems typically have to deal with large quantity of data and required options that cannot be solved in reasonable time by groups of specialist (Smith and Sonuc, 2011). Modelling tools will also assist in situation where the solution is required within a short time. Two typical modelling tools are Linear and Heuristic Programming.

In modelling, the optimisation problem may be represented using a mathematical model or programme that attempts to optimise the objective function subject to the constraints applied. If there are only linear terms in the objective function and the constraints, the technique used to formulate the mathematical model is called a Linear Programming (LP). Linear programming (LP) is one of the ubiquitous modeling tool used in optimiing the resources in wireless mesh network. The keys to linear programming are decision variables, objective and constraints.

LP is often used to model problem with only continuous variables such as deployment cost in the objective function. In problems that involve minimising or maximising number of electronic devices, integer variables are unavoidable. Binary variables used in problems that required decision on selection of locations can also be treated as integer variables. In such scenarios, Integer Linear Programming (ILP), which typically takes longer time to resolve, will be required. Mixed Integer Linear Programming (MILP) model is the obvious choice in problems related to optimisation of deployment cost of HOWBAN that often requires the selection of strategic location for installing the network devices.

The stages involved in solving the optimisation model using LP (Parkinson et. al., 2013; Smith and Sonuc, 2011) generally begin with identify the decision variables or the output or solution to the problems. An ohjective function or a statemet to relate the objective of the problem with the decision varibales will be followed. The objective function is formulated as a mathematical model for maximising or minimsing the objective. Optimisation problems have to deal with the limitation of the resources and technical or physical conditions. The limitations and conditions are classified as contraints to the optimisation problem. Ability to indentify and specify the constraints is pertinent to finding solutions for the optimisation problems. The summary of the stages involved in solving optimisation problem using LP is depicted in Table 3.1

Table 3.1: Solving optimisatin problem using Linear Programming

1	Generate an mathematical model or algorithm model of the problem Identify the decision variables. Decision variables are values that represent the output or solution to the problems. Some typical decision variables for wireless mesh network is number of routers and their installation sites. Write the objective function An objective function is a statemet to relate the objective of the problem with the decision varibales. The function may attempt to either minimise or maximise the objective. The objectives could be deployment cost, coverage area and network capacity. In wireless mesh network the typical objective functions include minimizing the deployment cost and maximising the coverage area. The decision variable could be the number of routers and their respective installation locations. Identify the constraints. Constraints are conditions that must be complied by a solution to an optimisation problem. They are used to indicate the limitation of the resources. Constraints may be values or conditions that restrict the range or boundary of possible solutions. Constarints are model mathematically using greater than or equal (≥) , equal (=) or less than or equal (≤) symbols. Some typical constraint in wireless mesh network is link distance between routers and number of routers, radio channels and number of hops. Logical constraints are used to indicate the validility of the link between a transmitter and a receiver. Non-negativity constraints that can help to avoid solutions that are not practical. For example the number of routers selected and the required bandwidth cannot be negative.
2	Solve the algorithm using Solver: Simple procedures such as Graphical method and Simplex method can be use to solve simple LP model. Branch and Bound method are available to solve more complicate LP or ILP and MILP model. For most practical problems, these procedures are executed using computer based solvers such as EXCEL solver, MATLAB, IBM CPLEX and AIMMS are typically used. IBM CPLEX is the most commonly used by academics in doing WMN research as it is free to use.
3	Solve the algorithm using Heuristics To reduce the simulation and produce a reasonably good approximate results, heuristics algorithm are typically deployed. For larger network size or network with many constraints, metaheuristic algorithm are required (Parkinson et al., 2013).

The optical backend of a HOWBAN network selected for the study of optimisation typically has an OLT located at the Central Office (CO). The CO is usually located at the centre of the specified coverage area. The OLT is connected to the Internet via the backhaul wired network. In TDM PON, feeder optical fibres radiate from the OLT to optical splitters, which act as remote notes (RN). ONU are connected to the output port of optical splitters via distribution optical fibres. The WR in the WMN front end of HOWBAN enable the clusters of mobile clients (TC) to be connected to the OLT. The TC are distributed randomly in the specified area. Some of the WR are used as GW that act as bridges between the WMN and the backend optical network. ONU are typically attached to the GW in order to reduce transmission loss and the length of the distribution fibres required.

In order to minimise the deployment cost, the WR has to be deployed strategically in order to minimise the number of WR required to provide coverage to all the TC at the required data rate. Thus the number of potential installation sites available for the WR will be specified as one of the constraints in optimisation model. The ability of TC to connect to WR at the desired data rate is constrained by the propagation loss. The same constraint is applicable to determine the communication ranges between WR and consequently the installation sites. Amongst the various propagation loss models available (See Section 2.3.1.1), the physical and protocol models are most commonly adopted by researchers.

For WMN that deployed Wi-Fi technology, different frequency bands are chosen for the WR to WR link and WR to GW link. The 2.4 GHz band is often used for communication between WR and WR. As GW received accumulated traffic from multiple WR within its communication range, the 5 GHz band that has higher bandwidth for carrying data is selected. Due to the broadcast nature of the radio transmission, the use of different frequency bands will help to eliminate radio interference in particular co-channel interference. The radio interference if occur will degrade the performance of the network.

More traffic can be carried if more non-overlapping radio channel frequencies are available. The 2.4 GHz band can accommodate 11 channels each with 20 MHz bandwidth. This frequency band has only 3 non overlapping channels; channel 1, 6 and 11. This implies that the radio channels have to be used repeatedly in the WMN and thus imposed the need to assign the channels carefully so as to avoid co-channel interference. Genetic programming is often used to resolve problems in channel assignment problem. A description of Clonal selection based genetic algorithm is given in Appendix A.

The siting of RN is crucial for reducing the distances from the ONU that are attached to the GW. The reduction in the distances will in turn reduce the length of the distribution fibre required and consequently lowering the deployment cost. The number of ONU that can be linked to the RN is determined by the fan-out or number of output ports of RN. This constraint put a limit on the number of WR that can be used as GW. Potential sites for installing RN will have to be specified in the model.

The total traffic can be carried by the optical fibre is constraint by the PON technology used. In EPON the downstream and upstream are symmetrical at 1.25Gbps where as in GPON 2.448 Gbps is available in the upstream and 1.2441 Gbps is available in the downstream (ITU-T, 2012; Skubic et.al., 2009)

Once the model of the problem is complete with optimisation objectives together with the required conditions and constraints, it can be presented to a solver to find the solutions. A survey of the available solvers or simulation tools are given in Appendix B.

3.3.3 Solving HOWBAN Optimisation Model

Simple procedures such as Graphical method and Simplex method can be use to solve simple LP model. Branch and Bound method are available to solve more complicate LP or ILP and MILP model. For most practical problems, these procedures are executed using computer based solvers. IBM CPLEX (IBM, 2015) is free to use by the students and academics and thus commonly used by academics involved in WMN research. The use of CPLEX to solve HOWBAN optimisation problem is breifly described here.

CPLEX is a commercial simulation tool commonly used to solve LP and related constrained optimisation problems. CPLEX optimisation solver consists of a library of subroutines that can be called or embedded into user's application programme. Primal simplex and dual simplex optimisers are two popular tools in CPLEX that are selected to solve LP model. MILP model can be resolve using the branch and bound algorithm in CPLEX.

The LP model and the variables required to solve the optimisation problem can be presented to CPLEX as a text file. In HOWBAN, the objective function may dictate that the cost of network deployment be minimise subject to the conditions that all mobile devices within the specified area must be connected to the Internet at some desired data rate. The variables and data that need to be declared for the optimisation solver may include:

- types of variables
- cost of optical and wireless devices
- cable laying and installation cost
- set of TC
- candidate sites for installing the OLT, ONU, WR and RN
- condition for selecting the installation sites
- condition of using WR as GW
- constraints on the link distance between wireless devices
- constraints on the radio channel available and fan-out of RN
- constraints on the data rate
- constraints on the number of optical and wireless devices

CPLEX allows the programme to be run interactively. However it will be more convenient to embed the subroutine of CPLEX in user's application programme for running the optimisation routine iteratively for various scenarios. The optimisation problems typically require the study of the relationship between the deployment cost with different settings of requirements and resources. The variables and data that need to be changed for each scenario may be presented as configuration files to CPLEX to ease the iteration process. Further elaboration on the use of CPLEX to solve the MILP optimisation model formulated for this research work is given in Chapter 5.

3.4 Issues on HOWBAN Optimisation and Survivability

Optimisation of networks to reduce deployment cost and ensure survivability are key concerns in the study of hybrid optical wireless network as can be observed in some of the most recent literature. Optimisation of placement of optical and wireless devices and laying of optical fibres is commonly used to evaluate deployment cost (Bhatt et al., 2015; Chowdhury et al., 2014; Liu et al., 2015; Tanzil and Farkas, 2016; Yu et al., 2014a; Yu et al., 2014b; Yu et al., 2017). Issues pertaining to single fibre failures are discussed in Yu et al. (2014a), Yu et al. (2014b) and Yu et al. (2017) while the focus of Bhatt et al. (2015) and Liu et al. (2015) is on multiple fibre failures. Survivability can be achieved using backup ONU (Bhatt et al.,2015; Yu et al., 2014a;   Yu et al., 2014b; Yu et al., 2017) and strategy to allocate dynamically the wireless and optical bandwidths (Liu et al., 2015).

In Chowdhury et al. (2014), the authors described four configurations of hybrid optical wireless networks and the optimisation strategy for greenfield deployment. All the configurations have a Passive Optical Network (PON) at the backend. The four options for the wireless front end are Wi-Fi only, Worldwide Interoperability for Microwave Access (WiMAX) only, combination of Wi-Fi and WiMAX and combination of Wi-Fi and LTE (Long Term Evolution). However, evaluation was only performed on optimal clustering of the mobile clients and placement of Evolved Node B (eNB) in a LTE network. The eNB acts as the Radio Base Station (RBS) in the LTE network to bridge the mobile devices and the Evolved Packet Core (EPC) that manages the connection of the eNB to the backbone. The aim of the optimisation is to minimise the average distance of the clusters of mobile clients to the attached eNB in order to reduce deployment cost and improve the quality of service in terms of available bandwidth and signal strength. The optimisation was evaluated using an Integer Linear Programming (ILP) model based on the distribution of mobile devices with no mobility and taking into account the channel assignment, co-channel interference and capacity constraints of eNB.

Connecting the backup ONU located at different segments of a hybrid optical wireless network in a mesh configuration in order to divert the traffic from the failed optical path in any of the segments for the survivability of the network is proposed in Bhatt et al. (2015). The proposed configuration attempts to improve the performance of networks where the backup ONU are connected in ring configuration. The investigation was performed based on four optical wireless segments each having a backup ONU. The backup ONU in the segments are linked using optical fibre. For the ring configuration, traffic from the failed optical path in any segment will be diverted wirelessly to its backup ONU. The backup ONU will divert the traffic to its peer located at its adjacent segments via the fibre link. Similar strategy is deployed for the backup ONU in the mesh configuration to handle the diverted traffic. If a segment in the ring configuration encounters fibre failure simultaneously with its adjacent segments, all the alternative paths for diverting the traffic will be cut-off. This scenario will not pose a problem to the mesh configuration where the backup ONU in each segment is provided with three alternative paths to divert the traffic. Some of the diverted traffic will be blocked if there is insufficient residual capacity in the adjacent segments. As the mesh configuration has more paths to divert the traffic, the traffic blocked will be less than that of the ring configuration as reflected in the results obtained from the simulations performed by the authors. The enhanced survivability and reduction in blocked traffic in the mesh configuration are achieved however at the expense of higher cost in providing additional optical paths to the mesh network.

In Tanzil and Farkas (2016), the authors aimed to minimise the cost of deployment of broadband access with capacity up to 50 Mbps by deploying wireless technology at the last mile in order to reduce the optical fibre length.

The reduction of the fibre length will decrease the high cost associated with the civil work in laying the fibre. Comparison was made on the deployment cost of Fibre-to-the-Node (FTTN) and Fibre-or-Air-to-the-Node (FATTN) scenarios. In FTTN, the feeder link between the central office (CO) and the front end is established using optical fibre. The distribution at the front end is done using either the legacy copper network or LTE wireless network. The distribution is done wirelessly in areas where the copper network is unable to fulfil the 50 Mbps link requirement. In FATTN, both the feeder link and the front end distribution are done wirelessly.

The minimisation of the deployment cost is based on the Connected Facility Location Problem model which employed mixed integer programming (MIP) and Steiner tree in Gollowitzer and Ljubic (2011). The MIP is used to optimise the deployment locations of the wireless routers to ensure that the wireless coverage area is accessible to the clients. Steiner tree where additional vertices or Steiner points may be added to the network graph is used to optimise the connection between the wireless routers. The results obtained indicate that the full wireless strategy in FATTN has a lower deployment cost but the short transmission range of the wireless link may pose a challenge in long reach deployment.

In Yu et al. (2014a), the wireless front end is used to divert the disrupted traffic from the primary ONU that is attached to a failed distribution fibre in a segment of a hybrid optical wireless network to the backup ONU located at other healthy segments of the network to ensure network survivability. The placement of the ONU and Wi-Fi routers in the network is optimised using both Integer Linear Programming and heuristic programming to provide maximum coverage and connectivity to the wireless clients in the network while minimizing the number of wireless routers and indirectly the deployment cost. The network survivability is guaranteed for single failure in the distribution fibres. In case of failure in one of the distribution fibres, the disrupted traffic will be diverted to the backup ONU using the wireless network. The primary ONU in each segment is assigned multiple backup ONU to provide network connectivity and ensure that the residual capacity of the backup ONU are able to absorb all the disrupted traffic. The network performance for a combination of various number of ONU, Wi-Fi routers and potential placement sites in different urban area scenarios was investigated.

In Yu et al. (2014b), the authors also optimised the placement of the wireless routers using Integer Linear Programming model and heuristic technique. The additional objective is to provide maximum coverage to the targeted clients while ensuring the network survivability due to single distribution fibre cut. The survivability is achieved by associating the primary ONU in each distribution segment of the hybrid optical wireless network with a backup ONU located at other segments. When the distribution fibre linked to a primary ONU is broken, the disrupted traffic will be rerouted to its backup ONU using the wireless mesh front end. Alternative wireless paths which are disjointed are assigned to the primary ONU to ensure the availability of wireless routers for the primary ONU to divert its disrupted traffic. The number of hops is included in the optimisation programme to restrain the transmission delay which is not considered in (Sarkar el al., 2007b). A combination of various number of ONU, wireless routers, jointed paths and hops were used to evaluate the network performance.

In Liu et al. (2015), the authors proposed a strategy where the allocation of wireless and optical resources or bandwidths is jointly assigned to guarantee availability of connection and network survivability under multiple fibre failures condition. The multiple fibre failures can occur when a share resource such as a conduit which carries multiple fibres is cut. To ensure the survivability of the network that is encountering multiple fibre failures, each source router is assigned a primary and a secondary connection path to the OLT. The source router is tasked to transmit the traffic from the clients attached to it to the OLT. The primary and secondary paths must fulfil the wireless and optical bandwidth and connection availability requirements of the source router. Both the primary and backup paths can be shared by different source routers if the connection constraint can be fulfil in order to reduce the resources required. The wireless and optical bandwidths in each path are apportioned to carry both the primary and backup traffic from multiple source routers. In normal condition, the n^{th} source router in the network will transmit its traffic via its primary path. If the primary path of the n^{th} source router is disrupted due to multiple fibre failures, its traffic will be rerouted to the preassigned backup connection path. The action is successful only if 1) the backup path of the n^{th} source router is in normal condition, 2) other source routers which share the backup path with the n^{th} source router are in normal condition and does not compete for the same backup resources and

3) the primary wireless paths of other source routers which share the wireless bandwidth of the backup path of the n^{th} source router can discharge their allocated wireless bandwidth to the n^{th} source router. The investigation was performed by formulating an ILP model to minimise the bandwidth demand by optimising jointly the optical and wireless resources. The results obtained show that the strategy is able to reduce the wireless and optical bandwidth requirements compared to the dedicated resource allocation strategy used in Correia et al. (2009).

In Yu et al. (2017), the authors employed an ILP model to minimise the deployment cost of a hybrid optical wireless network while providing the desired capacity without undue delay to an urban environment even when one of the distribution fibres failed. Minimisation of the cost to provide maximum coverage is achieved by optimising the locations for siting the passive optical components, ONU and the wireless routers together with the fibre and wireless paths in the network. The study was performed using an area of 6 km square which is divided into 36 equal plots. The area is served by an OLT and two feeder fibres. The network survivability was investigated based on the condition where only one distribution fibre can fail at any one instant. Instead of providing backup distribution fibre to address the fibre failure, the traffic from the failed distribution fibre is rerouted to the backup distribution fibres using the preassigned backup wireless paths and ONU in the network to preserve network connectivity and reduce the cost to mitigate the effect of fibre failure. The capacity and the delay constraints are taken into consideration in the placement of the components in the optical distribution network and the wireless routers in conjunction with the survivability strategy.

Table 3.2: Summary of work by various authors on HOWBAN survivability

Author	Objective	Strategy
Bhatt et al. (2015)	Mitigate multiple fibre failure survivability.	Divert the traffic from the failed optical path using backup ONU located at different segments of a hybrid optical wireless network in a mesh configuration.
Chowdhury et al. (2014)	Minimise deployment cost and improve the quality of service in terms of available bandwidth and signal strength.	Minimise the average distance of the clusters of mobile clients to the attached eNB.
Liu et al. (2015)	Mitigate multiple fibre failures survivability.	Allocate dynamically the wireless and optical bandwidths.
Tanzil and Farkas (2016)	Minimised the cost of deployment.	Deploying wireless technology at the last mile to reduce the optical fibre length.
Yu et al. (2014a)	Minimised deployment cost while providing maximum coverage and connectivity Mitigate single fibre failure survivability	Placement of backup ONU and Wi-Fi routers Wireless front end is used to divert the disrupted traffic to the backup ONU at other healthy segments of the network
Yu et al. (2014b)	Provide maximum coverage Mitigate single fibre failure survivability	Placement of the backup ONU and wireless routers
Yu et al. (2017)	Minimise the deployment cost while providing the desired capacity without undue delay to an urban environment. Mitigate single fibre failure survivability	Optimising the locations for siting the passive optical components, ONU and the wireless routers together with the fibre and wireless paths in the network.

The work of the authors discussed above are summarised in Table 3.2 As can be observed from Table 3.2, the focus of all the authors are on the components of HOWBAN. The issues on power outage and backup power which have not been probed will be discussed in Chapter 4.

CHAPTER 4

PRIORITISING REDUNDANT NETWORK COMPONENT FOR HOWBAN SURVIVABILITY USING FMEA

4.1 FMEA Method and Strategy

Deployment of redundant components is the ubiquitous practice in improving the reliability and survivability of a network due to node and link failures. Numerous studies have been done to evaluate the impact of node failure and strategies to resolve the problem. The work done so far indicated the broadband access network operators has full control of all the resources and solutions to resolve the failures in the network except for failures due to grid power outage which is usually under the purview of the electricity utility providers. Most studies are aimed at evaluating the impact of providing redundant resources in specific segment of the HOWBAN on network availability and survivability. No formal tools have been used to enable the evaluation and decision to prioritise the deployment of redundant facilities in the network. This research work differs from others in that it identifies and prioritises the critical segment and the redundant component that need to be deployed to ensure network survivability by adapting the Failure Mode Effect and Analysis (FMEA) method.

Failure Mode Effect and Analysis (FMEA) method which is commonly used in the manufacturing sector is a quality method designed to anticipate potential failure modes and prevent failures. In this research, the Failure Mode Effect and Analysis (FMEA) method is adapted to identify the potential failures in the network infrastructure and weigh the impact of the failures for prioritising the redundant facilities to be deployed. The intrinsic feature of FMEA systematic technique to assess risks and preventive measures to assure reliability is deemed fitting for the proposed evaluations of the hybrid optical wireless broadband access network (HOWBAN).

Deploying redundancy in the network will inevitably incurred additional CAPEX and OPEX (Hajduczenia et al., 2012) but it is essential to mitigate the indirect cost of network failure in terms of non-compliance with service level agreement and loss of revenue from related services. FMEA technique can be used to help reduce the cost of redundancy by identifying and prioritising the critical redundant component needed in the network.

FMEA is employed in engineering to specify, discover and remove predictable and plausible faults from a system in order to improve its reliability (Bono et al, 2003; Creveling, 1956; Goel and Graves, 2007; IEEE 2002; Krasich, 2009; Pecht and Nash 1994).

Reliability is a measure on the probability of a system or in this case a network, accomplishing its planned function in the required duration and operating environment (Goel and Graves, 2007). FMEA helps to analyse and overcome different failure modes that may affect the reliability of a system or in this instance the hybrid optical wireless broadband access network prior to its implementation (Goel and Graves, 2007). Failure mode and failure effects are two key evaluation criteria used in FMEA. Failure modes are ways where the network fails to provide reliable and uninterrupted service to its clients. The failure modes may be due to failure of network components, intermittent operation, partial or total loss of service (DOA, 2006). Failure effect focuses on the effects of failures on the network function. The FMEA tools provide a foundation to identify potential failure modes due to deficiencies in the network. Typical FMEA evaluation forms are given in DOA (2006) and ReliaSoft (2003). In this research work, FMEA is used to evaluate the reliability of both the functional and hardware components of a hybrid optical wireless broadband access network.

FMEA hinged on Risk Priority Number (RPN) for root causes of the potential failure modes to appraise the risk of the system and prioritise the actions that need to be taken (Goel and Graves, 2007). A Risk Priority Number (RPN) is derived for each root cause by multiplying their respective severity, occurrence and detection rating (Sydney Water, 2010; WMG, 2007).

$$\text{RPN} = (\text{Severity}) \times (\text{Occurrence}) \times (\text{Detection})$$

A root cause of a potential failure with higher RPN indicates it will create higher risk to the network if left unattended. Thus priority will be given to corrective actions recommended for potential failure that is associated with the highest RPN.

A rating of 1 to 10 is typically used to rate the severity of the root causes for the failure on the network performance and the frequency of occurrence. Fatal impact and inevitable occurrence will be rated with a score of 10 while the lowest score of 1 reflect meagre impact and extremely unlikely occurrence (ReliaSoft, 2003; Sydney Water, 2010; WMG, 2007). The severity and occurrence rating criteria in FMEA are normally based on various specifications associated with reliability of electronic hardware equipment particularly MTTR (Mean Time To Repair) and MTBF (Mean Time Between Failure) (IEEE, 2010; ITU-T, 2016a; Susan, 2012).

The detection rating scale of 1 to 10 is used to rank the capability or ease of the network to detect the root causes of the potential failures modes identified. A score of 1 will be allotted to network designed to detect with certainty the causes of failures while network without features to detect the causes of failures will be placed on the highest end of the scale.

After determining the RPN, actions will be recommended to reduce the RPN for each root cause. The severity, occurrence and detection ratings are then re-evaluated based on the recommended corrective action to mitigate the failures. The new RPN for each root cause is then calculated and used to analyse the risks presented by the causes of failures and prioritise the corrective actions to be taken.

4.2 FMEA Method for HOWBAN

In order to prioritise redundant network component for HOWBAN survivability using FMEA, the severity, occurrence and detection ratings have to be determined. The method for assigning severity, occurrence and detection rating scale before and after the recommended mitigation actions for HOWBAN will be explained in the next section. Following that a discussion on the results obtained using the FMEA method will be presented.

4.2.1 Severity Rating Scale

A score of 1 to 10 is used to reflect the severity of the failure of a component to the performance of the HOWBAN. The severity is rated based on number and duration of MC unable to connect to OLT as a result of component failures in a segment of the network. Failure in network component that is closer to OLT will affect more MC compared to those at the front end and tends to result in higher severity. One of the specifications of a network component that can be used to determine the duration of the failure is Mean Time To Repair (MTTR) which determine how soon the network will recovered after experiencing system failures (ITU-T, 2016a; Krasich, 2009; Susan, 2012). In an operational system such as the HOWBAN, repair often means replacement of hardware module (Susan, 2012). Replacement of outside plant and customer premise equipment may need to consider delivery and field work time and is typically rated as between 8 to 24 hours or more (Chen et al., 2010; CORDIS, 2011; Hajduczenia et al., 2012; ITU-T, 2016a).

In this paper, the duration of failure is based on MTTR of each of the component. IEEE standard (IEEE, 2012) quoted that for repair or part replacement in the central office, a couple of hours is required. Typical MTTR adopted by telecommunication sector is 4 hours (China Telecom, 2016; ITU-T, 2016a). For outside plant, the MTTR is set at 24 hours (ITU-T, 2016a).

A higher severity rating indicates the increase in the severity of the failure based on the number of MC affected by the failure in the network components and the time taken to rectify the failure. A rating of 10 is assigned to OLT failure where all MC are unable to access the Internet. Rating 1 is allocated in condition where all MCs are able to connect to Internet via the OLT.

MC will not be able to connect to OLT when there is failure in WR due either to equipment fault or power outage in the WR/MC segment. WR which failed but required shorter time to repair is rated lower than the WR failure that needs longer time to repair. Thus WR failure with 1 hour disconnection time is given a rating of 2 while that created 4 hours of disconnection time has a rating of 3.

As GW in the GW/WR segment is typically connected to several WR, when failed, it will affect larger number of MC and is thus given a higher severity rating compared to WR failure. Gateway failure creating disconnection time of 4 hours is also rated higher with rating of 5 than GW failure that has 1 hour of disconnection time which has a rating of 4. Since the impact of ONU failure in the ONU/GW segment is the same as GW, they are given the same rating. Distribution fibre (DF) failure is accorded higher rating compared to ONU and GW failures as it typically required more time to locate and clear.

Failures in Optical splitter and feeder fibre (FF) are rated higher than DF, ONU and GW as their failures will have impact on relatively more MC. The severity rating set up is as shown in Figure 4.1.

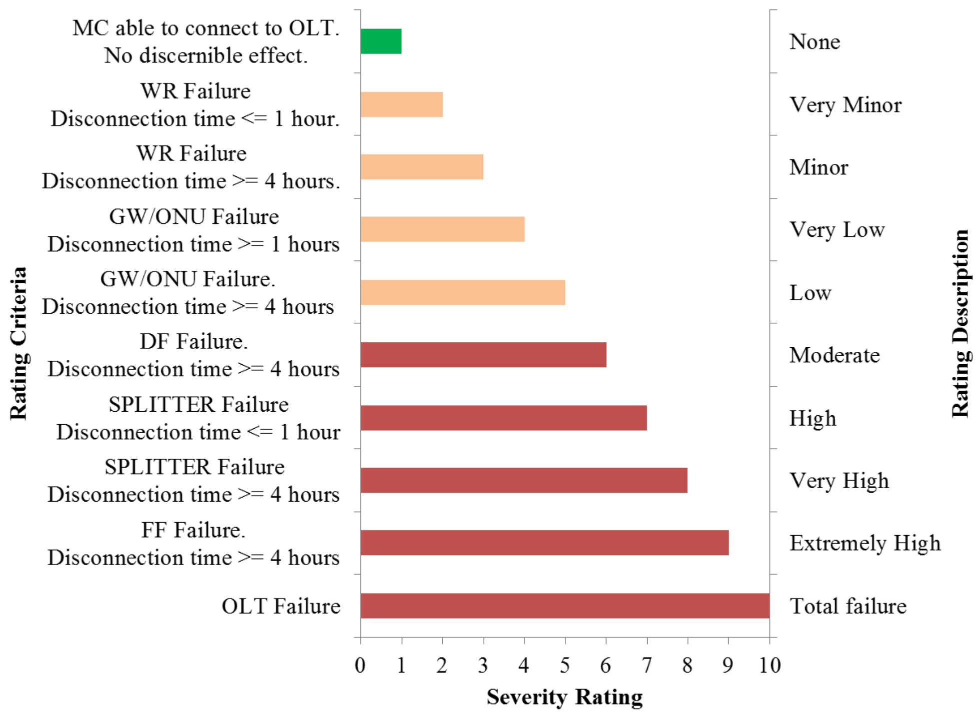


FIGURE 4.1: HOWBAN Severity Rating Scale.

The failure percentage of the passive components in the passive optical network is more than 7 times that of active components and Mean Time Between Failure (MTBF) is at least 10 times higher (Hajduczenia et al., 2012) as shown in Figure 4.2 implied that the backend optical network is more resilient than the front end wireless in terms of equipment failure.

OLT is typically located at central office (CO) and is well protected with redundancy to bring it back into operation within 50 ms (Hirose et al., 2010), thus its resiliency is considered comparable to passive component. It is thus reasonable to focus the evaluation on the faults due to the active components in segments from ONU to WR located at the front end.

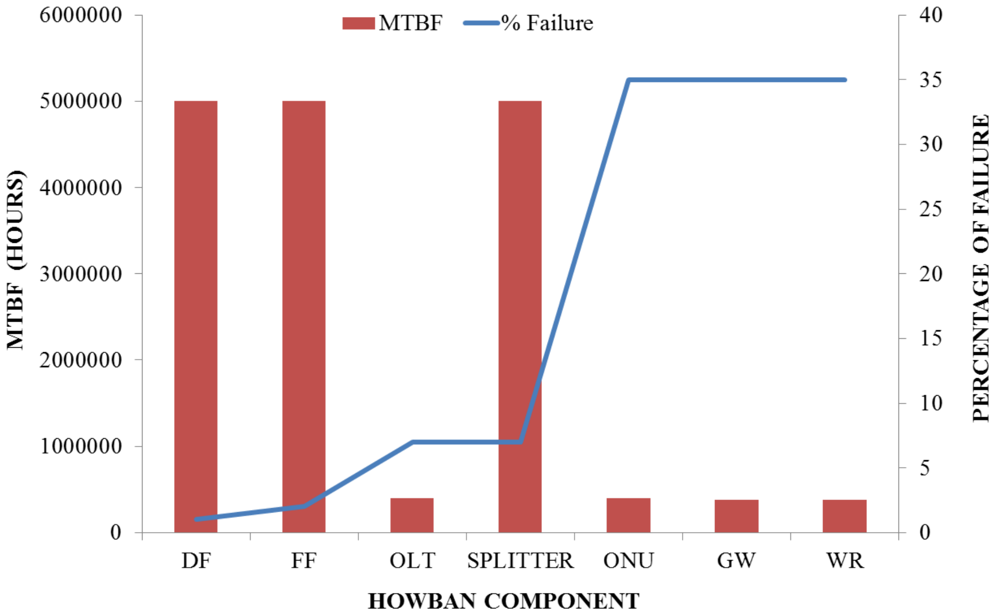


FIGURE 4.2: Comparison of MTBF and Failure Statistics of network component.

The MTTR for all the components from ONU to WR segment are similar since they are all located outdoor thus their severity rating will just depend on the number of MC affected. In this research work, the worst case rating with highest disconnection time is taken for WR, GW and ONU which are rated 3, 5 and 5 respectively to calculate the RPN.

FMEA required that corrective actions to be recommended after the severities of the components on the network failure have been assigned and to re-rate the severity factor after the performing the corrective actions. In this thesis, potential failure due to network component at the front end will be resolved by employing the ubiquitous approach of installing redundant components. Backup battery is recommended for resolving the potential failure due to grid power outages. With single redundant parallel stand by equipment installed, the severity factor will be reduced by around half assuming that the equipment will survive to 50% of its rated MTBF (Billinton and Allan, 1992; Speaks, 2010). The severity rating for WR, GW and ONU are thus re-rated or revised to 1, 3 and 3 respectively.

4.2.2 Occurrence Rating Scale

In severity rating, the same impact on MC is felt whether the failure is due to equipment fault or power outage thus both are given the same rating. For occurrence rating, the scale for network component fault and power outage in HOWBAN has to be separated as they have difference failure criteria.

The commonly considered specifications for occurrence rating of the HOWBAN network component is Mean Time Between Failure (MTBF) (ITU-

T, 2016a; Krasich, 2009; Stanley, 2011). Mean Time Between Failure is the average time between failures of a product and is frequently quoted in hours. As MTBF is the inverse of failure rate it can thus be used to indicate the occurrence of the failure in the network component (ITEM, 2007; McLeish, 2010; Susan, 2012). A relative score range of 1 to 10 is preferred rather than the absolute probability as an absolute probability of 10^{--6} may give the perception that failure occurring is very remote (WMG, 2007). A fault that is almost certain to occur will be rated with a score of 10. In this paper, the network component occurrence rating scale will rely on MTBF of each of the component. A higher MTBF value is associated with low occurrence.

Typical MTBF of various components in the HOWBAN listed in Table 4.1 are quoted from CORDIS (2011), ITU-T (2016a) and commercially available devices. ONU, GW and WR which has MTBF ranging from 380000 hours to 400000 hours or between 40 to 50 years is assigned a rating of 5. OLT is grouped together with the passive devices which have MTBF above 80 years and is assigned a relatively low rating of 1. Although OLT has lower MTBF compared to the passive components in the network, its failure rate is low because it is located at the central office and is typically protected with ample redundancy. This common policy enhances the resiliency of OLT and makes its failure percentage similar to that of passive optical splitter in the network. Components with MTBF of less than 1 year are given a rating of 10.

Table 4.1: MTBF of Network Components.

Component	MTBF (Hours)	MTBF (Years)
OLT	400000	46
FF	5000000	570
SPLITTER	5000000	570
DF	5000000	570
ONU	400000	46
GW	380000	43
WR	380000	43

The relative occurrence rating of network component in HOWBAN is set up as shown in Figure 4.3. The rating is consistent with the optical network and outside distribution network failure statistics collected by China Telecommunication Corporation (Hajduczenia et al., 2012) as shown in Figure 4.2 which showed that the failure percentage of passive devices and OLT are much lower than the front end components.

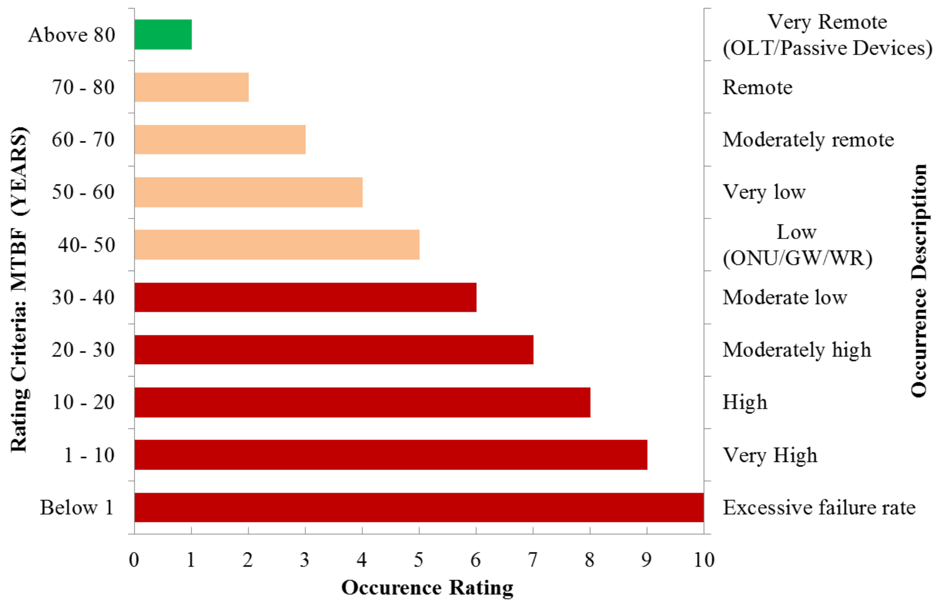


FIGURE 4.3: HOWBAN Equipment Failure Occurrence Rating Scale.

The occurrence rating for power failure or outage is based on frequency and duration of grid power outage product using the data reported in World Bank enterprise survey as shown in Figure 4.4 (World Bank, 2016). The highest and lowest frequency and duration of power outage product value derived are 114.4 hours and 0.16 hour respectively. The highest product values per month is experienced by less developed countries in Middle East & North Africa while the high income Organisation for Economic Co-operation and Development (OECD) countries has the lowest product value. Relatively high product value also occurred in South Asia and South Saharan Africa economy compared to the high income countries.

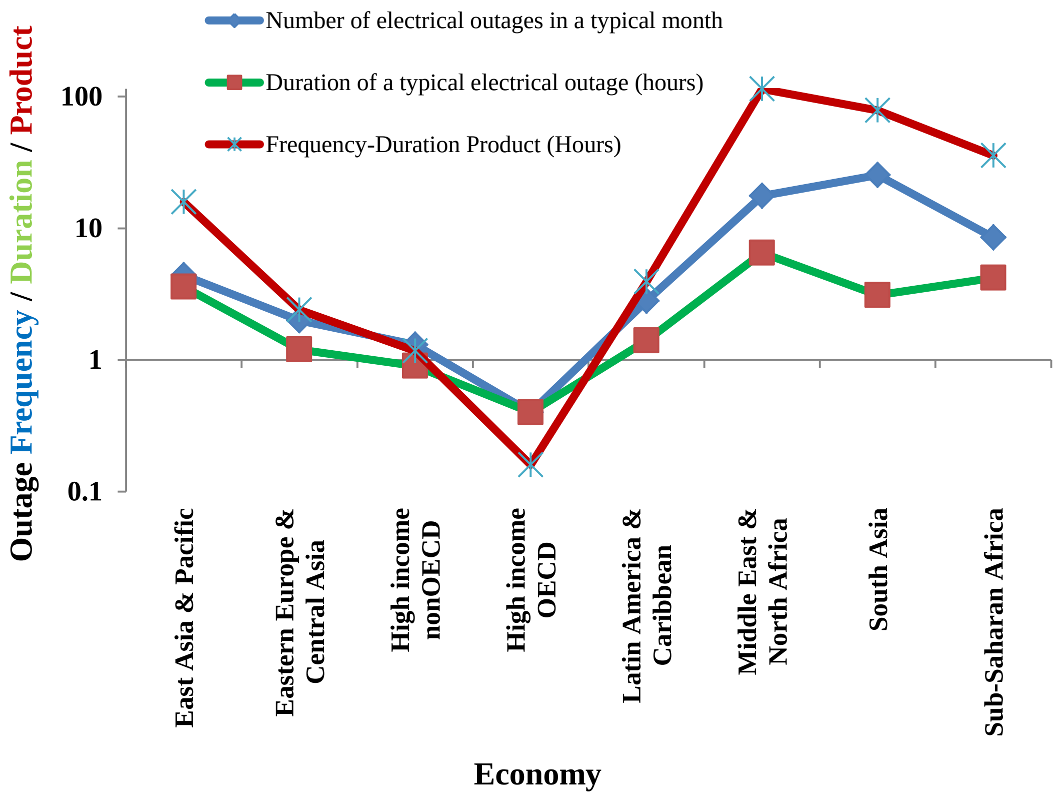


FIGURE 4.4: Power Outages Data.

The minimum rating of 1 and maximum rating of 10 is based on the lowest and highest product value derived by multiplying the frequency and average duration of power outages of each economy. The rating scale is as shown in Figure 4.5. The frequency outage product value above 90 hours is assigned a rating of 10 and a rating of 1 will be accorded to product value below 1 hour.

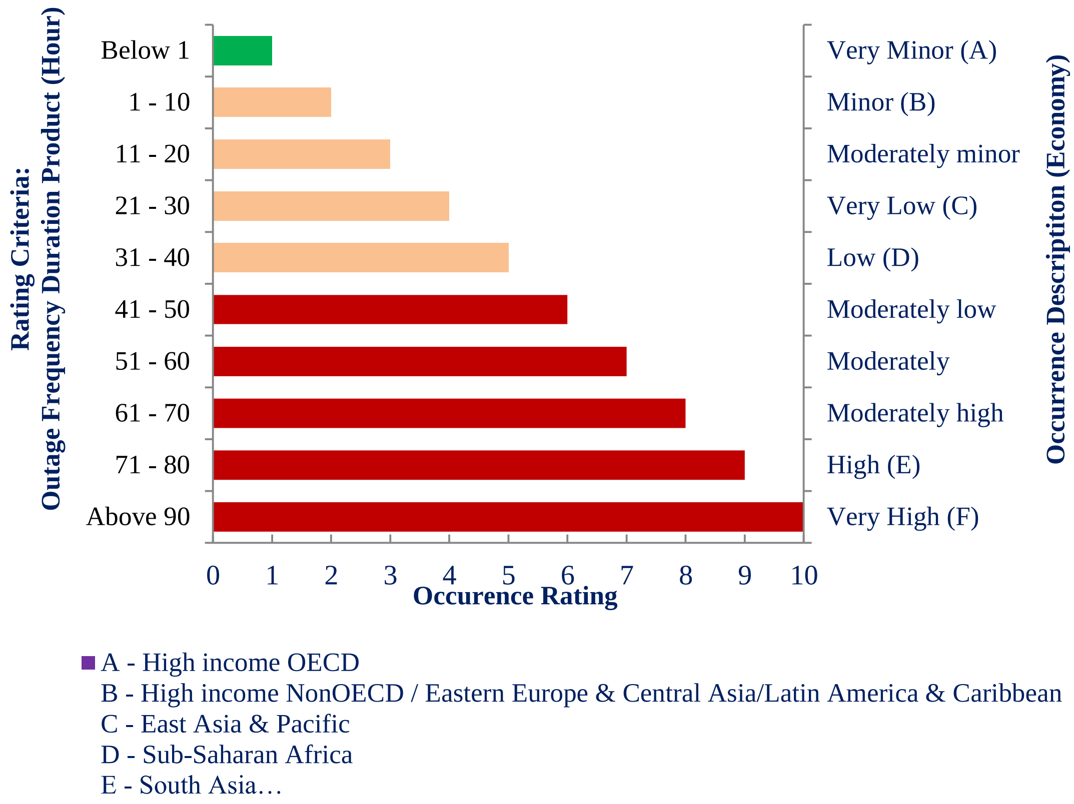


FIGURE 4.5: HOWBAN Power Outages Occurrence Rating Scale

ITU reported that as at 2014, the number of broadband users per 100 inhabitants is 83.7 and 21.1 in the developed and less developed countries respectively (ITU, 2015a). This reflects that there is greater potential for growth and need to expedite the deployment of broadband access to the less developed countries thus this FMEA evaluation will be based on the less developed economies listed in World Bank (2016). As the quality of the grid power in the less developed economies is very poor, the occurrence for failure due to loss of power in HOWBAN is given a rating of 10.

The rating of the occurrence after provision of redundant parallel stand by component or backup battery is half that before taking the recommended actions so as to be consistent with assumptions made for the severity rating.

4.2.3 Detection Rating Scale

Detection of optical network failure typically relied on using optical time-domain reflectometer (OTDR) to sense the loss of upstream signal (Wong, 2014). Faults in HOWBAN can be detected effectively with the availability of improved monitoring and network fault detection strategy such as centralized failure detection system (CFDS) (Ab-Rahman et al., 2009) coupled with recently introduced IEEE SIEPON standard ((Hajduczenia et al., 2012). In SIEPON standard, the absence of REPORT/GATE message pair for a duration 50 ms will indicate a link fault. Continuous monitoring of transmission from OLT by ONU shortened the delay in sensing the link fault. The data link from OLT is assumed failed if the valid optical signal is not received within 2 ms after a device is detected and registered in the network. For the wireless mesh network, the multipath nature of the network will enable failed node to be detected and traffic re-routed to alternative route. With the improve monitoring and detection standard failures in the optical backend and robustness of the wireless mesh network, failure in HOWBAN can be reliably detected and thus given a rating of 1 in this thesis. The detection rating scale is displayed in Figure 4.6.

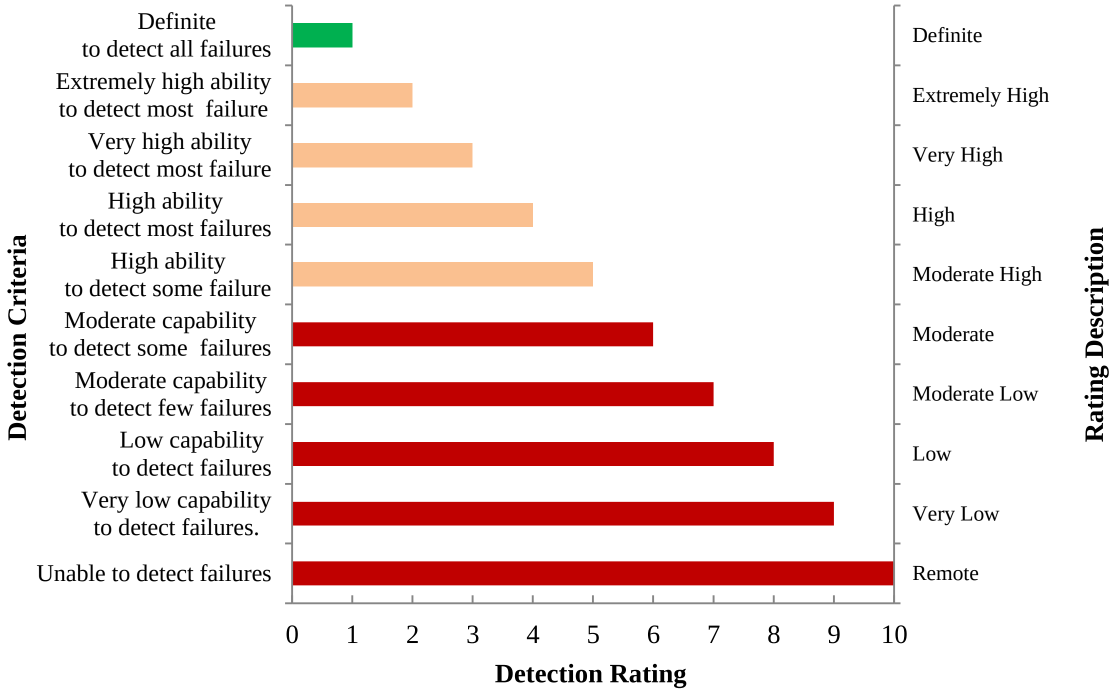


FIGURE 4.6: HOWBAN Detection Rating Scale.

4.3 FMEA method results and discussion

The process function identified is to provide connection to Internet via HOWBAN as stated in the first column in Table 4.2 which is adapted from FMEA evaluation form. The second column merely lists the numbering of the segments at the front end of HOWBAN. The segments that constitute the network will be listed in the third column of Table 4.2. The network segments may include those in the backhauls and the front end. Total failure of all components in any segment of the HOWBAN will result in total link loss between MC and OLT under the unprotected optical network. However it is extremely unlikely that all components in any segment will completely fail and thus it will be more realistic to evaluate the scenario of partial link loss which is due to partial failure in segments within the network. As explained in Section 4.2.1, the resiliency of the network component in the backhaul is much higher than those at the front end thus this evaluation will be focused on the front end. The relevant front end segments viz. ONU/GW, GW/WR and WR/MC are as noted in the third column in Table 4.2.

For the ONU/GW segment, the potential failure mode identified is GW unable to access the ONU which is connected at its back end as depicted in the first row of the fourth column in the table. The effect of this failure is that traffic from access points (WR) connected to the GW is unable to be forwarded to the OLT thus creating Partial Link Loss in the network as shown in the first row of the fifth column in the table. The severity rating of 5 is assigned to the effect of this failure using the rating scale in Figure 4.1. The rating is recorded in the first row of the sixth column in Table 4.2.

Two root causes for this failure mode identified are ONU failure due to equipment faults and loss of power as shown respectively in the first and second row of the seventh column in Table 4.2. The severity, occurrence and detection rating assigned in Section 4.2.1 to 4.2.3 for each of the root cause are inserted into the respective row from eighth to tenth column in Table 4.2.

The RPN for both of the root causes calculated are then recorded in the first and second row of the eleventh column in Table 4.2. The recommended actions that can be taken to reduce the severity, occurrence and detection rating and consequently the RPN for each root cause are entered into the respective row in the twelfth column in the table. Based on the recommended actions to be taken, the severity, occurrence and detection rating for each of the root cause will be revised. The new ratings are recorded in respective row in the thirteenth to fifteenth column in Table 4.2. The new RPN are derived and inserted into the respective row in the last column in the table.

The procedure to calculate the RPN is repeated for the potential failure modes for each of the remaining segments identified. The RPN for all the roots causes in all the segments are then used to analyse and identify the potential failure mode and root causes that need priority attention. The full result of the FMEA technique used to analyse the partial link loss scenario in HOWBAN in as shown in Table 4.2.

The results in Table 4.2 are plotted in Figure 4.7. It is evident from the data presented in Figure 4.7 that the RPN associated with power failures or outages before taking mitigation action; indicated by the cross hatched bar with green boarder, are double that due to equipment failure. It can also be observed that with the provision of redundant equipment and backup power their respective RPN can be reduced by at least 3 times. However, the RPN due to power outages remained higher than that of equipment failure even after mitigation. The high reliability of the communication equipment linked to high MTBF is a factor that equipment failures are associated with lower RPN compared to power outages in all situations.

Table 4.2: FMEA Table for Partial Link Loss.

Process Function	No.	Network Segment	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s) / Mechanism(s) of Failure	Sev	Occ	Det	RPN	Recommended Action(s)	**Partial Redundancy**			
												Sev	**Occ**	**Det**	**RPN**
To provide connection to Internet via HOWBAN	1	ONU /GW	GW unable to access ONU	Partial Link Loss (PLL)	**5**	ONU failure: ONU lost power	**5**	**10**	**1**	**50**	Backup battery	**3**	**5**	**1**	**15**
						ONU failure: Equipment failed	**5**	**5**	**1**	**25**	Redundant ONU	**3**	**2**	**1**	**6**
	2	GW/WR	WR unable to access partial GW	Partial Link Loss (PLL)	**5**	GW failure: GW lost power	**5**	**10**	**1**	**50**	Backup battery	**3**	**5**	**1**	**15**
						GW failure: Equipment failed	**5**	**5**	**1**	**25**	Redundant GW	**3**	**2**	**1**	**6**
	3	WR/MC	MC unable to access partial WR	Partial Link Loss (PLL)	**3**	WR failure: WR lost power	**3**	**10**	**1**	**30**	Backup battery	**1**	**5**	**1**	**5**
						WR failure: Equipment failed	**3**	**5**	**1**	**15**	Redundant WR	**1**	**2**	**1**	**2**

Sev: Severity; Occ: Occurrence; Det: Detection

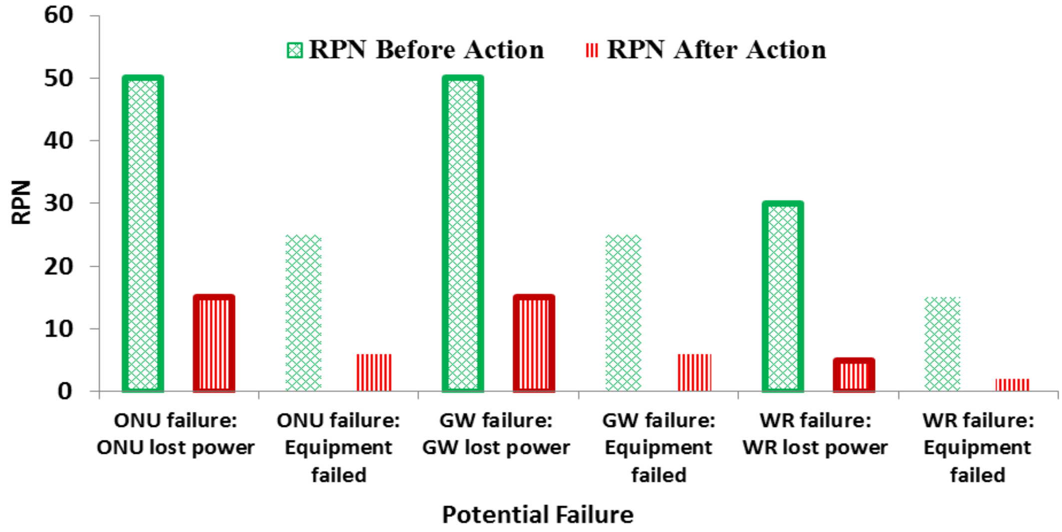


FIGURE 4.7: Partial Link Loss RPN Before and After Mitigation.

This finding is in line with concerns on power outages raised in report on electricity reliability by Pacific Power Benchmarking Report published by Pacific Power Association (PPA) in June 2015 which showed that average SAIDI (System Average Interruption Duration Index) which reflects the average amount of time that customers are interrupted has increased from 592 minutes per customer in 2001 to 5664 minutes per customer in 2012 (PPA, 2015). Studies conducted by Ashok et al. (2012) highlighted the deficiency in the reliability of the power grid in India where the typical power outage may be 2 to 8 hours a day in urban area and may exceed 20 hours a day in rural area re-affirmed the scenario of power outages given in the Enterprise Surveys conducted by the World Bank as shown in Figure 4.4 (World Bank, 2016).

The power outages could be due to unreliable electrical power transmission and distribution system (Al-Muhaini et al., 2010; Ashok et al., 2012) and badly design substation (Xu et al., 2002). Consequently backup power supply is inevitable for the HOWBAN especially for the front end WR which are located at remote areas and less developed countries with unreliable or no grid supply. The backup power system typically consists of combination of standalone power system such as battery and diesel generators (Ashok et al., 2012; Chowdhury et al., 2012; Thomas and David, 2000). The backup battery cost is 0.5 USD/Ampere hour while the typical 10 kVA diesel generator is 6000 USD (Chowdhury et al., 2012). Battery performance and life cycle is sensitive to temperature which has to be kept at around 27°C (Ashok et al., 2012; CPUC, 2008). The backup battery solution is more expansive for the outside plant due to the harsh temperature environment which required energy for cooling and thus leading to considerable increase in its deployment cost compared to the same solution for the central office (Ashok et al., 2012; CPUC, 2008; Thomas and David, 2000).

Battery bank either Lead Acid or Lithium type are commonly used to provide the power during power outage. However for extended period of power outages in excess of 8 hours, the battery will be fully drained and need to be recharged. Clearly the battery is able to maintain the HOWBAN operation during outages but the duration is limited. Typical best practice of reserve power in WR in a developed country is quoted as minimum of 4 hours with an objective of 8 hours in CPUC (2008) while Ashok et al. (2012) highlighted that backup power is required to support daily outages of 2 to 8 hours in urban area and up to 20 hours in rural areas. To use the battery to support the network power for longer period of time will increase the cost significantly (Ashok et al., 2012; CPUC, 2008; Moury et al., 2012). Diesel generator is recommended to support outage period exceeding 8 hours.

The redundant power source must be capable to sustain communication for MC and network monitoring between the various segments in the network (CPUC, 2008). Backup power system using diesel generator not only involved CAPEX but also OPEX which include cost of the running fuel and maintenance cost (Ashok et al., 2012; Chowdhury et al., 2012; Nema et al., 2010). A more detailed study on the cost for the provision of backup power to enhance and optimise the reliability and survivability of HOWBAN is essential for extending the network especially to rural areas and less developed countries which encounter uncertainty in quality of grid power.

4.4 Implications of the results

This research has highlighted that the grid power failure occurrence is twice that due to equipment failure in all the segments at the front end of HOWBAN thus resulting in the corresponding higher value of RPN. RPN for grid power failure is reduced by deploying backup battery but the value remained higher relative to that of equipment failure due to the low quality of the grid power particularly those in rural areas and less developed economies compared to the high MTBF of the equipment. It is plain that backup power supply is critical for the deployment of HOWBAN especially in rural areas and less developed countries and investigations entailing the optimisation of deployment cost for backup power in HOWBAN are crucial. The studies will assist to hasten the decision for rendering affordable broadband internet access to empower the deprived community to access the Internet and narrow the digital divide gap which has been identified by ITU as one of the key factors to raise the economy of a nation leading to improvement in the quality of life of people in the world. As wireless communication is also one of the key enablers for Internet of things which is essential for the successful realisation of smart city initiatives there is a need to give impetus to embark on the optimisation study proposed. Failure to address the grid power issue in the rural areas and less developed countries will continue to hinder the progress in the broadband penetration.

Although FMEA is usually deployed before the network is implemented, it must be kept in mind that the variables used in determining the RPN is not constant and may vary under different working environment. It is thus essential to review the FMEA process at regular intervals in line with changes in the technology. Nevertheless FMEA provides an engineering approach to obtain a good overview of the network performance.

CHAPTER 5

IMPACT OF BACKUP POWER IN OPTIMISING DEPLOYMENT COST OF HOWBAN WITH SURVIVABILITY

5.1 HOWBAN backup power

It is highlighted in Section 2.1 that one of the key strategies to remove poverty is to furnish internet access using broadband to the communities. The communities living in remote area and unable to receive supply of electricity are denied the connection to the online world. Results obtained in Chapter 4 have identified that one of the deficiencies in the infrastructure is the lack of reliable power grid which is the main factor affecting the survivability of hybrid optical wireless broadband access network (HOWBAN). Although backup power can be installed to mitigate the problem, the implication is that the capital expenditure will increase. In the studies of the deployment cost optimisation by Lee et al. (2011), it was concluded that survivability is of utmost importance and will be of grave concern if not undertaken at the design stage. The studies also concluded that there is a compromise between network deployment cost and network survivability. This part of the research evaluates the effect of the costs of backup power on sustaining survivability of a HOWBAN network which has not been done before.

5.2 Reference HOWBAN Architecture

The reference architecture of HOWBAN used in this research is shown in Figure 5.1. The hybrid optical wireless network is able to mitigate the high deployment cost of a full optical network by incorporating a wireless front end (Sarkar et al., 2007a). Wireless mesh network using Wi-Fi technologies that provide up to 1 GHz bandwidth access using the various 802.11 Wi-Fi technologies (INTEL, 2017b) is a ubiquitous option for the front end of hybrid optical wireless broadband access networks. The provision of larger bandwidth will make available more spectrum and radio channels to support more clients. The mobile clients or devices in the data traffic concentration points (TC) can be connected to the Internet via either wireless routers (WR) or gateways (GW) within their radio range. Traffic from wireless routers will be routed to a wireless gateway either directly or through other wireless routers in a multihop manner. The multihop feature enables the communication range of a wireless router to be extended and provide the resilient and self-healing characteristics associated with wireless mesh networks. Each wireless gateway is connected to an optical network unit (ONU) which is connected via optical fibre to an optical splitter unit which acts as remote note (RN). The remote note is linked using optical fibre to an optical line terminal (OLT) which is located at the central office (CO). While the fibre backhaul of HOWBAN from ONU to OLT is able to furnish the large bandwidth desired, the wireless front end will facilitate the continued strong demand for mobile access (ITU 2015b).

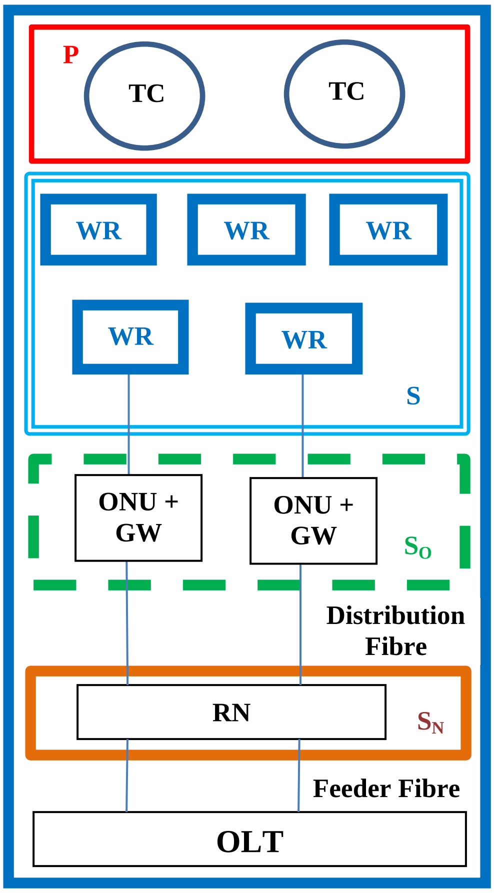


Figure 5.1: Reference HOWBAN Architecture.
OLT: Optical Line Terminator RN: Optical Splitter
ONU: Optical Network Unit GW: Gateway Router WR: Wireless Router
TC: Data Traffic Concentration Point P: Set of TC
S: Set of potential WR Sites S_N: Actual/Discrete RN sites
S_O: Actual/Discrete GW sites with ONU installed

5.3 Evaluation Strategy

It has been shown that the deployment cost of hybrid optical wireless networks is dominated by the cost of civil works for deploying fibre at the back end (Lee et al., 2011) and the survivability is determined mainly by the unreliable grid power especially at the front end (Chan et al., 2017). Motivated by these findings, the investigation is done to determine the feasibility of replacing the front end of a HOWBAN having a full survivability network (FSN) configuration with an alternative path network (APN) configuration where the reliability of the wireless nodes are enhanced by backup power. This research work also weighed the impact of backup power on the deployment cost of a wireless mesh network with survivability. The evaluation strategy is depicted in Figure 5.2.

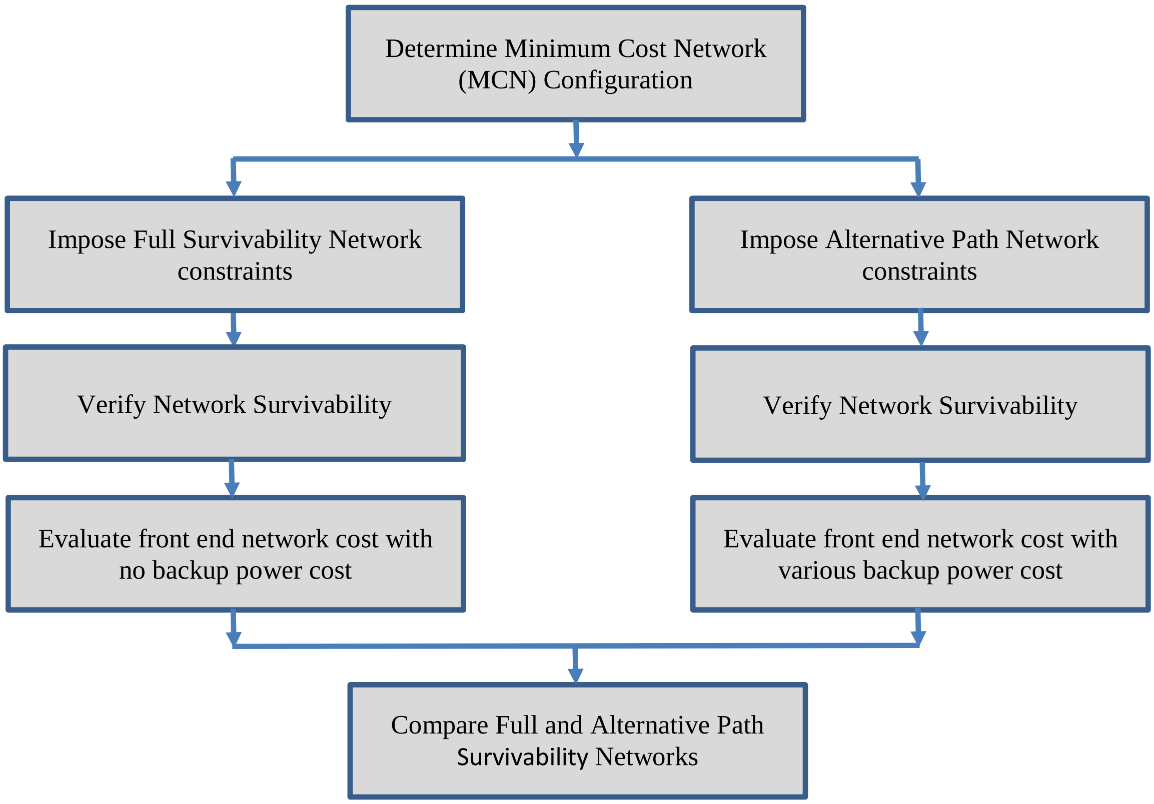


Figure 5.2: Evaluation Strategy.

The evaluation is performed using IBM CPLEX optimisation software. The full survivability model is derived from a Minimum Cost Network (MCN) based on Lee et al (2011). The alternate path is based on Dijkstra's shortest path algorithm. The design specifications and mathematical formulation are described in Section 5.3.3.

5.3.1 Full Survivability Network

This study is based on the network architecture depicted in Figure 5.1. The traffic demand from data traffic concentration points (TC) distributed over the deployment area are satisfied by the IEEE 802.11 wireless routers (WR) and gateways (GW). The gateways are connected to their respective optical network unit (ONU). The optical network units are linked to an optical splitter which acts as remote note (RN). The remote note is served by two geographically independent optical fibres linked to an optical line terminal (OLT) sited at the central office (CO). The objective is achieved by jointly optimising the optical and wireless devices in the network as well as traffic routing at the optical backhaul. The full survivability network is derived from a minimum cost wireless mesh network (MCN) in Lee et al. (2011).

The optimisation constraint imposed on MCN is that each TC is connected to at least a WR/GW and the traffic demand distributed over the deployment area can be fulfilled. The full survivability network (FSN) is then derived by imposing an additional constraint that no link will be affected by failure in any of the wireless devices in the optimised minimum cost network (MCN). Verification of the network survivability is then performed to determine the percentage of survivability of the full survivability network configuration.

A benchmark called MCNCOST is created using the minimum cost network for evaluating the impact of backup power on the network deployment cost and survivability. The MCNCOST is derived by considering the costs of the front end wireless nodes with no backup power in the minimum cost network (MCN). The full survivability network cost (FSNCOST) is determined based of the costs of the front end wireless nodes without backup power in the full survivability network (FSN).

5.3.2 Alternative Path Network

For the alternative path survivability scenario, the additional constraint imposed on the minimum cost configuration (MCN) is that each node in the minimum cost network configuration (MCN) must have at least one alternative transmission path. The survivability of this alternative path network (APN) is then evaluated. The alternative path network cost (APNCOST) is determined based of the costs of the front end wireless nodes without backup power in the alternative path network (APN). Backup power is then installed at the nodes of the alternative path network and the APNCOST with various backup power costs are determined. The APNCOST obtained are used to compare with that of the FSNCOST to assess the feasibility of replacing the FSN with an APN deployed with backup power.

Algorithm chosen to resolve shortest path issue is typically based on Dijkstra's algorithm (Dijkstra, 1959) where the network is represented as a graph. The algorithm is commonly applied in both wired and wireless communication networks (Cheney, 1988; Hsu et al., 2008; Li et al., 2006; Luo et al., 2014; Musznicki et al., 2012; Williams et al., 2014). In this research, Dijkstra's algorithm is adopted to ensure that each node in the alternative path network has at least one alternative path. The algorithm for determining the alternative path based on Dijkstra's algorithm is depicted as below:

Let's:

V = set of nodes in min cost network;

V' = set of nodes in the alternative path network;

r = gateway node of the min cost network.

1. *V'* = *V*
2. Visit each of the nodes in *V* using the Depth First search.
   2.1. Let's *v* in *V* be the node being visited at current iteration.
   2.2. Mark *v*'s parent node (*v.parent*) from *V'*.
   2.3. Calculate the shortest path from *v* to *r* on *V'* by using Dijkstra's algorithm; ignore marked node in the calculation.
   2.4. Add the new nodes introduced in the shortest path into *V'*.
   2.5. Unmark *v*'s parent node (*v.parent*) in *V'*.
   2.6. If all nodes in *V* are visited, exit; Else, continue with 2.1.

5.3.3 Design Specifications and Mathematical Formulation

The reference scenario is a 2 km square area where the OLT is assumed to be located at the center. Tests have been run for 100, 200, 300, 400, 600, 800 and 900 TC randomly deployed in the square area with 200, 300, 400, 500 potential sites for installing wireless devices (S). The number of potential installation sites for ONU/GW (S_O) and remote nodes (RN) are set to

10% of the TC and 10 respectively. The instances are solved using IBM's solver CPLEX 12.6.3.

The cost of the devices are normalized to that of an ONU where OLT Cost (C^L), WR cost (C^R) and GW installation cost (C^G) are rated as 1000, 60 and 100 respectively. The range of the backup power cost (C^{BP}) is from 1 to 60. The device and trenching cost for RN at site k to ONU at site j (C_{jk}^O) and for RN at site k to OLT (C_k^N) are both rated at 500/km. The fixed assets consist of one unit of OLT, one unit of optical splitter and two feeder fibres.

The maximum wireless transmission rate; Γ and maximum optical transmission rate; Γ^0 are set to 54 Mbps and 1.25 Gbps respectively. The optical splitter fan-out (F_0) is assumed to be 32 and each node has 3 wireless interfaces.

The maximum transmission range (r) between TC and WR/GW is 100 m with data rate at 1Mbps while that for the backhaul links (between WR and WR; WR and GW) is 500 m. The data rate (D_i) between wireless devices for transmission radius of 50 m, 80 m, 100 m, 200 m and 250 m are set to 54, 48, 36, 12 and 6 Mbps respectively.

Assignment of WR/GW to TC is based on Λ_i which is an ordered subset that list the distances of active WR/GW from each TC. TC is assigned to the nearest active WR/GW.

The objective function is given as:

$$min \sum_{j\in S}(C^R + C^{BP})\mu_j + \sum_{\substack{j\in S_O \\ j\in S_N}}\left(C^G + C^O_{jk} + C^{BP}\right)v_{jk} + \sum_{k\in S_N}(C^L + C^N_k)Q_k$$

Subject to

$$\sum_{j\in S}\lambda_{ij} = 1 \qquad \forall_i \in P \tag{5.1}$$

$$\lambda_{ij} \leq \begin{cases} \mu_j & j\in \wedge_i \\ 0 & otherwise \end{cases} \qquad \forall_i\in P,\ j \in S \tag{5.2}$$

$$\mu_j + \sum_{\substack{m\in\wedge_i \\ \phi_{(m)} \geq \phi_{(j)}}} (\lambda_{im}) \leq 1 \qquad \forall_i\in P, \qquad j \in S \tag{5.3}$$

$$\gamma_{lj} + \gamma_{jl} \leq \begin{cases} \Gamma\mu_l & j\in\psi_i \\ 0 & otherwise \end{cases} \qquad \forall(l,j) \in S\times S \tag{5.4}$$

$$\gamma_{lj} + \gamma_{jl} \leq \begin{cases} \Gamma\mu_j & j\in\psi_i \\ 0 & otherwise \end{cases} \qquad \forall(l,j) \in S\times S \tag{5.5}$$

$$\sum_{i\in P} D_i\lambda_{ij} + \sum_{l\in S}\left(\gamma_{lj} - \gamma_{jl}\right) = 0 \qquad \forall j \in S\backslash S_O \tag{5.6}$$

$$\sum_{i\in P} D_i\lambda_{ij} + \sum_{l\in S}\left(\gamma_{lj} - \gamma_{jl}\right) - \sum_{k\in S_N}\gamma_{jk} = 0 \qquad \forall j \in S_O \tag{5.7}$$

$$\sum_{j\in S_O}\left(\gamma_{jk} - \gamma_k\right) = 0 \qquad \forall k \in S_N \tag{5.8}$$

$$\sum_{i\in P} D_i \leq |I_j|\left(\sum_{i\in I_j}\frac{1}{R_{ij}}\right)^{-1} + M_j\left(1-\mu_j\right) \qquad \forall j\in S \tag{5.9}$$

$$\sum_{l\in S}\left(\gamma_{jl} + \gamma_{lj}\right) \leq N_I\Gamma \qquad \forall j\in S \tag{5.10}$$

$$\sum_{j\in S_O}\gamma_{jk} \leq \Gamma^{\,0}\varrho_k \qquad \forall k\in S_N \tag{5.11}$$

$$\sum_{k\in S_N}\gamma_{jk} \leq N_I\Gamma\sum_{k\in S_N}\gamma_{jk} \qquad \forall j\in S_O \tag{5.12}$$

$$\sum_{k\in S_N}\gamma_{jk} \leq \mu_j \qquad \forall j\in S_O \tag{5.13}$$

$$\sum_{k \in S_N} \gamma_{jk} \leq 1 \qquad \forall j \in S_O \qquad (5.14)$$

$$\gamma_{jk} \leq \varrho_k \qquad \forall j \in S_O, k \in S_N \qquad (5.15)$$

$$\sum_{k \in S_O} \gamma_{jk} \leq F_0 \varrho_k \qquad \forall k \in S_N \qquad (5.16)$$

$$\lambda_{ij}, \mu_j, v_{jk}, \varrho_k \leq \{1, 0\} \qquad (5.17)$$

Constraint (5.1) ensures that a TC_i is always assigned to a wireless device which is an active and nearest device (ordered subset Λ_i) as given in Constraints (5.2) and (5.3). Constrain (5.3) also ensures that the number of WR; $\phi_{(j)}$, connected to the RN does not exceed the fan out; $\phi_{(m)}$, of the optical splitter. A wireless link can only be achieved when both transmitter and receiver are selected. The total uplink and downlink traffic must not exceed the maximum wireless transmission rate, Γ. This is achieved by constraints (5.4) and (5.5). Constraints (5.6) to (5.8) are flow balance constraints for TC to WR, WR to GW and ONU to OLT respectively. Constraint (5.9) limits the total access traffic of TC_i which is subject to the degradation of data rate due to the interference between TCs using the same channel and distance from wireless access point. I_j is the data rate of radio channel *I* used at site *j*. R_{ij} is the distance between the interfering radios from the wireless access point using the same radio channel which will cause degradation of the data rate. M_j is a constant that ensures that the inequality is maintained when $\mu_j = 0$. Constraints (5.10) and (5.11) assure the maximum flow for a wireless device and an ONU. N_I is the number of wireless interfaces per node. Constraints (5.12) to (5.15) force active devices to be installed at either end to form a wireless optical interface. Constraint (5.16) ensures that the traffic through the passive optical network (PON) is within its capacity Γ^0. Constraint (5.17) defines the binary variables to indicate valid wireless link between TC and WR, installation of WR, GW and RN respectively.

In order to evaluate the survivability of the front end of the HOWBAN network, this research work makes use of the Mixed Integer Linear Programming (MILP) model described earlier in which the objective function is to maximise the number of TC in which their connectivity and bandwidth are fulfilled when one of the network node fails:

$$max \sum_{\substack{i \in p \\ j \in s}} \lambda_{ij}$$

subject to

$$\sum_{j \in s} \lambda_{ij} \leq 1 \qquad \forall i \in P \tag{5.18}$$

In this model, the location of the optical nodes and wireless nodes have already been found (denoted with a 'prime' sign), except that λ_{ij} still remains as a decision variable as it may re-establish new connection when their existing serving node (WR or GW) fails. Thus for constraints (5.2) to (5.12) the changes will be as below:

$$\mu \rightarrow \mu', \;\; S \rightarrow S', \;\; S_N \rightarrow S_N', \;\; S_O \rightarrow S_O'$$

5.4 Impact on network cost and survivability

The investigation is started by optimising the number of nodes chosen for the minimum cost wireless mesh network (MCN). The cost of the network nodes is used as the basis to investigate the impact of backup power on the network cost of the full survivability (FSN) and the alternative path network (APN).

Two approaches are being investigated in our simulation. The first approach is to compare the deployment cost of minimum cost, full survivability and alternative path network configurations by considering the number of nodes required for each configuration. The minimum cost network configuration is used as the benchmark to compare with the full survivability and the alternative path scenarios. The second approach is to install backup power at all the nodes in the alternative path network to enhance the reliability of the nodes and determine the deployment cost of the network nodes. The deployment cost obtained is then compared to that of the full survivability network configuration with no backup power.

Figures 5.3 to 5.6 show the cost of the nodes required for full survivability, alternative path and minimum cost network configurations for various number of potential installation sites (S) for placing the routers (WR). The node costs are normalized to that of an ONU. The potential WR installation sites (S) selected ranges from 200 to 500 as depicted in Figures 5.3 to 5.6 respectively. The number of TC ranges from 100 to 900 for each potential WR installation site (S) scenario.

As can be observed from Figures 5.3 to 5.6, the cost of the nodes required for the front end of the minimum cost network configuration is the lowest compared to the full survivability and the alternative path configurations for all S and TC scenarios. The front end cost of the alternative path network is very close to that of the minimum cost network while that of the full survivability network is much bigger than that of the minimum cost network.

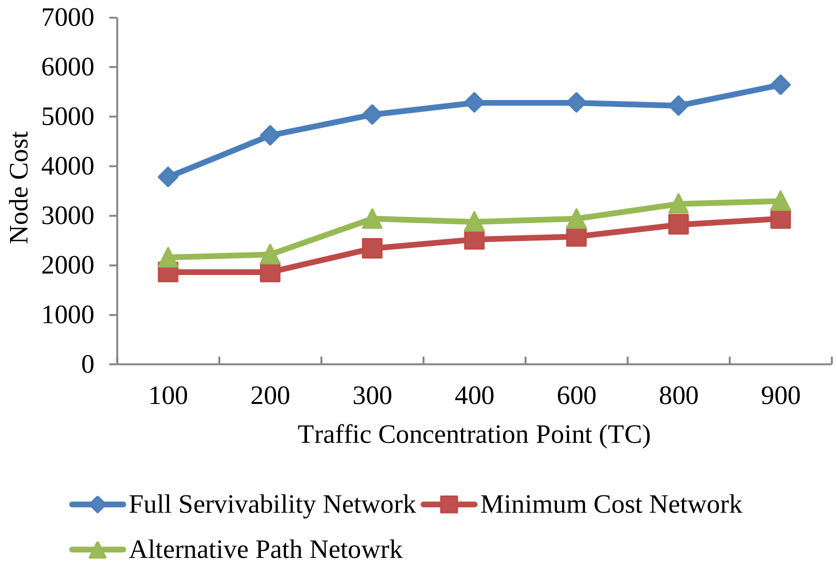


Figure 5.3: Node Cost normalized to that of an ONU for 200 Potential WR Installation Sites.

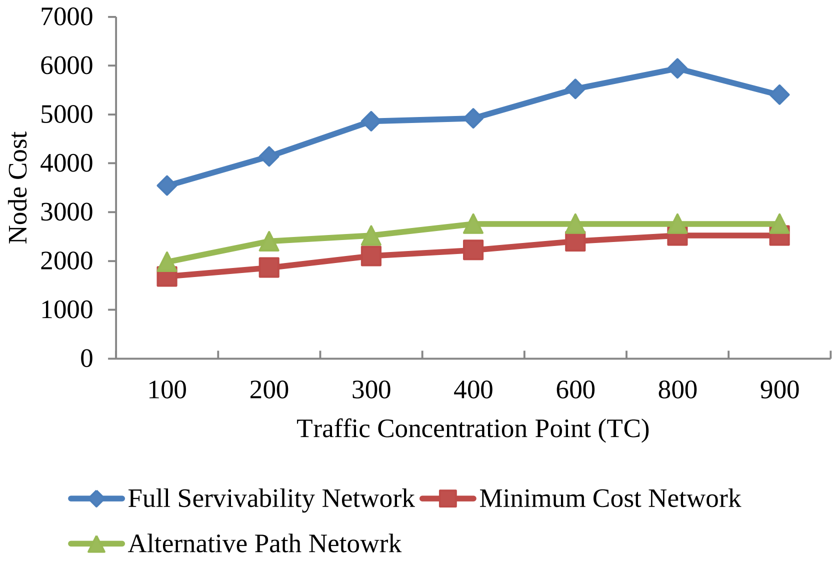


Figure 5.4: Node Cost normalized to that of an ONU for 300 Potential WR Installation Sites.

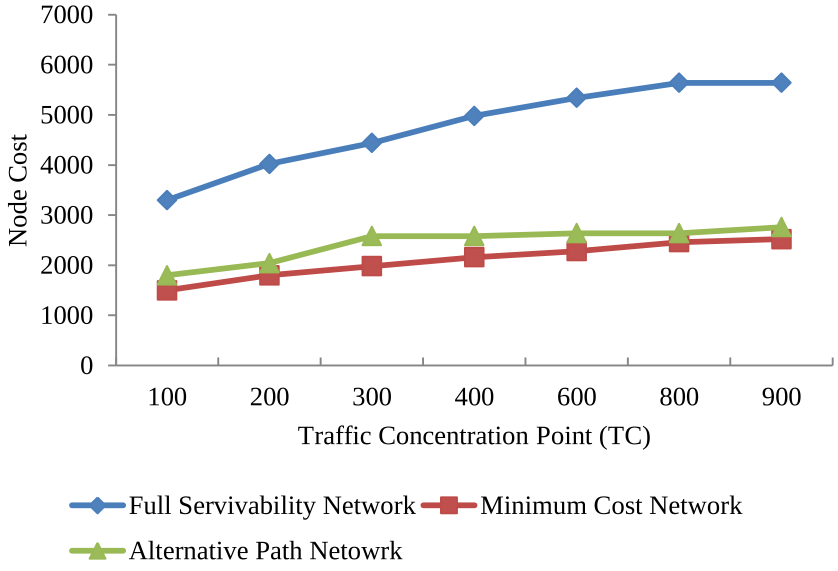


Figure 5.5: Node Cost normalized to that of an ONU for 400 Potential WR Installation Sites.

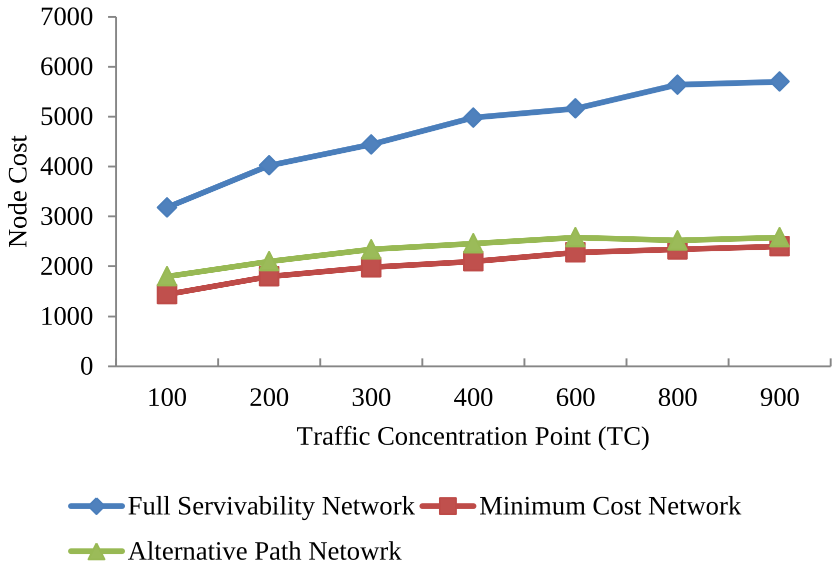


Figure 5.6: Node Cost normalized to that of an ONU for 500 Potential WR Installation Sites.

Figure 5.7 links the average percentage cost of deploying the nodes in each of the network configurations with potential WR installation sites (S) ranging from 200 to 500 using the average node deployment cost of the minimum cost network as the benchmark. The average node cost for each potential WR installation sites (S) scenario in the minimum cost network is derived by averaging the node cost for all the associated TC scenarios. The figure shows that the average percentage cost of nodes for achieving full survivability is 106% to 131% higher than that required for the minimum cost network. For the alternative path network, the percentage of cost increase ranges from 14% to 17% to that of the minimum cost network. The average percentage cost of the full survivability network is 106 % higher than that of the alternative path network.

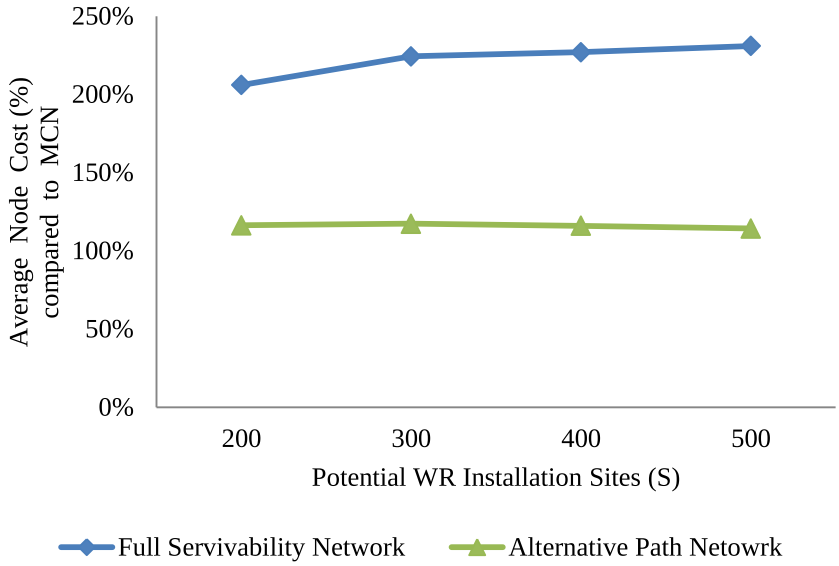


Figure 5.7: Average cost of nodes for FSN and APN compared to that of MCN

Figure 5.8 shows the results of the survivability verification tests done on the full survivability and the alternative path configurations. The percentage difference in survivability between the two network configurations corresponding to the 200 potential WR installation sites (S) scenario is derived by averaging the differences in survivability of the associated TC scenarios ranging from 100 to 900. The same procedure is applied to the other potential WR installation site (S) scenarios. The graph in Figure 5.8 shows that the survivability of the alternative path network (APN) for the 200 potential WR installation sites (S) scenario is 1.5% less than that of the full survivability network (FSN). The difference is shown to be relatively low for all other scenarios of potential installation sites for the wireless routers (S). The average difference is 1.93%.

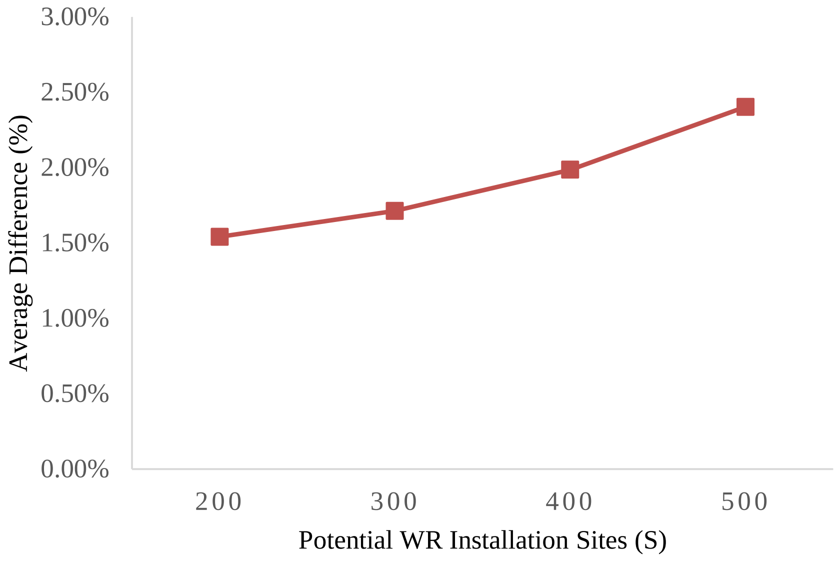


Figure 5.8: Average Percentage Difference in Survivability between FSN and APN.

The results obtained imply that the alternative path configuration is able to provide notable cost benefits without sacrificing the survivability significantly compared to the full survivability counterpart provided that the nodes in the alternative path configuration do not fail. This node failure problem can be resolved by installing backup power at all the nodes in the alternative path network as it has been shown that the survivability and reliability of the hybrid wireless optical broadband access network can be improved significantly by the installation of backup power particularly in remote areas and least developed countries (Chan et al., 2017). This finding forms the basis to investigate and compare the effect of the installation of backup power on the deployment cost of the alternative path configuration with that of the full survivability configuration where no back power is installed. Backup power is not considered for the full survivability configuration as each node has multiple alternative paths for communication.

Figures 5.9 to 5.12 show the differences between the network cost of the full survivability configuration with no backup power installed and that of the alternative path configuration with backup power installed at each of the nodes. The backup power cost ranges from 1 to 60 times that of the normalized ONU cost were evaluated. The 1x, 15x, 30x and 60x scenarios indicate that the cost of the backup power installed at each of the nodes in the alternative path network is 1, 15, 30 and 60 times that of the normalized ONU cost. The number of traffic concentration points (TC) selected ranges from 100 to 900. The potential installation sites (S) for the wireless routers ranges from 200 to 500 as depicted in Figures 9 to 12 respectively.

It can be deduced from Figure 5.9 that the difference between deployment cost of the front end of the alternative path network and that of the full survivability network is highest when backup power with a cost of one time that of the normalized ONU are installed at the nodes of the alternative path network by virtue of the position of the1x line in the figure for all TC scenarios. The positive difference hovering around 40% indicates that there is significant cost saving in adopting the alternative path configuration. The 15x line in Figure 5.9 indicates that each of the nodes in the alternative path network is installed with a backup power having a cost 15 times that of the normalized ONU. The difference between the cost of the full survivability network and the alternative path network is narrowed but still present a considerable cost saving as indicated by the positive difference. Cost saving can still be discerned even when backup power cost is 30x. As can be observed in Figure 5.9, cost saving is attainable provided that the backup power cost does not exceed 60x. Similar results are obtained for scenarios with 300, 400 and 500 potential installation sites (S) for wireless routers as shown in Figures 5.10 to 5.12 respectively.

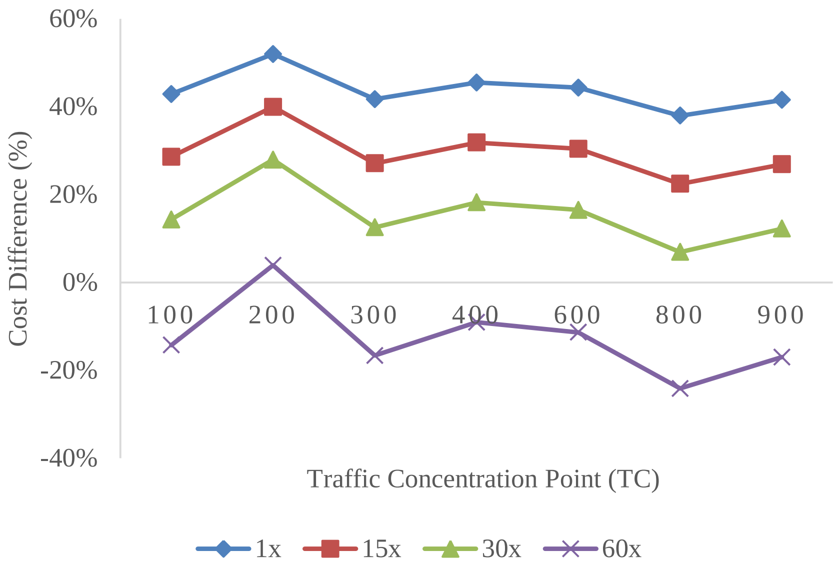


Figure 5.9: Cost Difference between FSN and APN for 200 Potential WR Installation Sites.

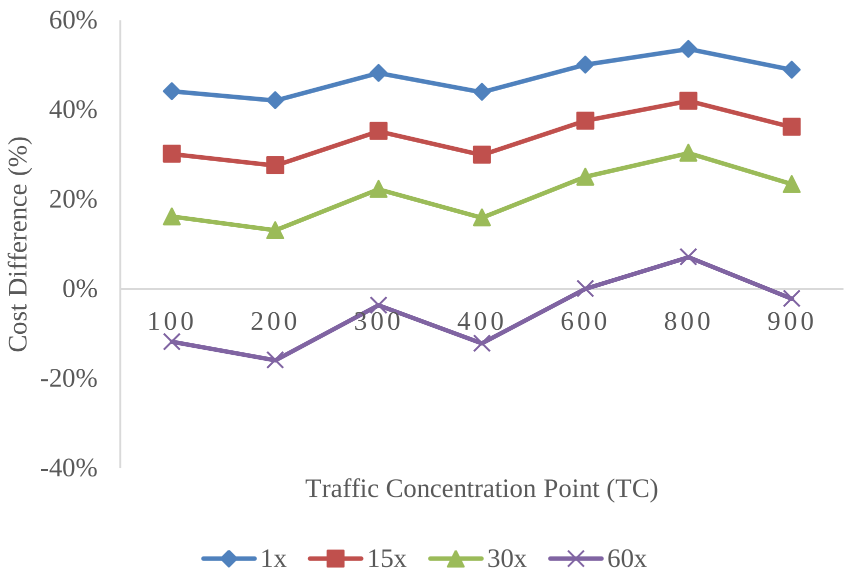


Figure 5.10: Cost Difference between FSN and APN for 300 Potential WR Installation Sites.

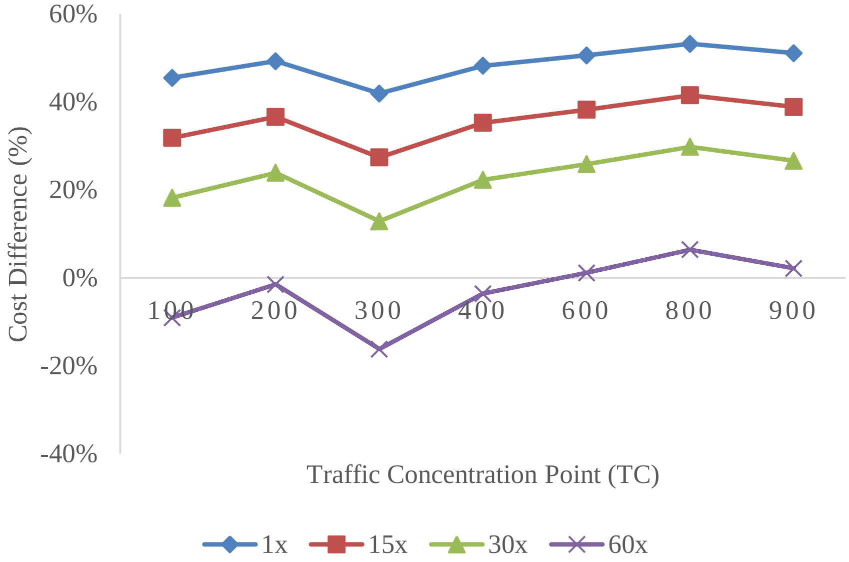


Figure 5.11: Cost Difference between FSN and APN for 400 Potential WR Installation Sites.

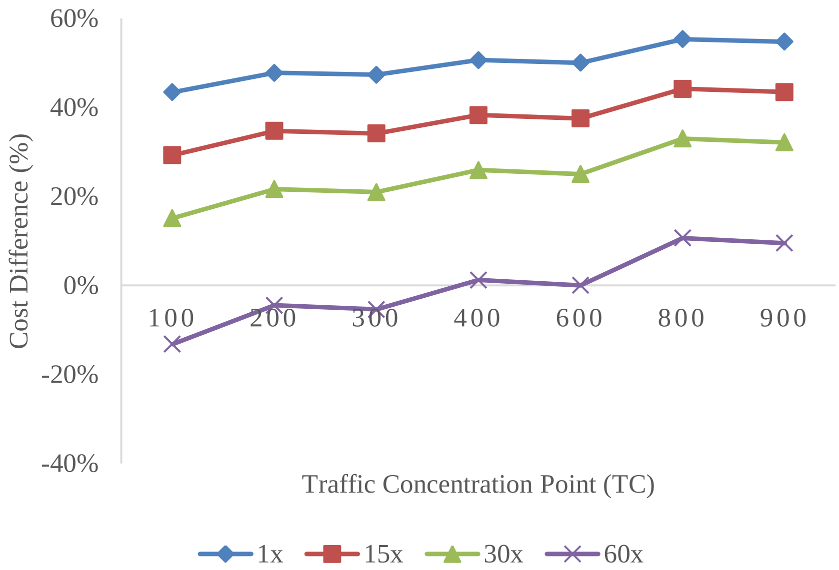


Figure 5.12: Cost Difference between FSN and APN for 500 Potential WR Installation Sites.

Figures 5.9 to 5.12 also reflect the trend that as the potential WR installation sites (S) for wireless routers increases a higher backup power cost can be accommodated to achieve saving in the deployment cost. The trend is clearly shown in Figure 5.13 where positive slope is depicted in each of the potential WR installation sites (S) scenarios. The average cost saving that can be achieved with backup power cost ranging from 1 to 30 times the normalized cost of an ONU is 34 %, thus showing great potential for implementing the alternative path configuration with backup power as proposed.

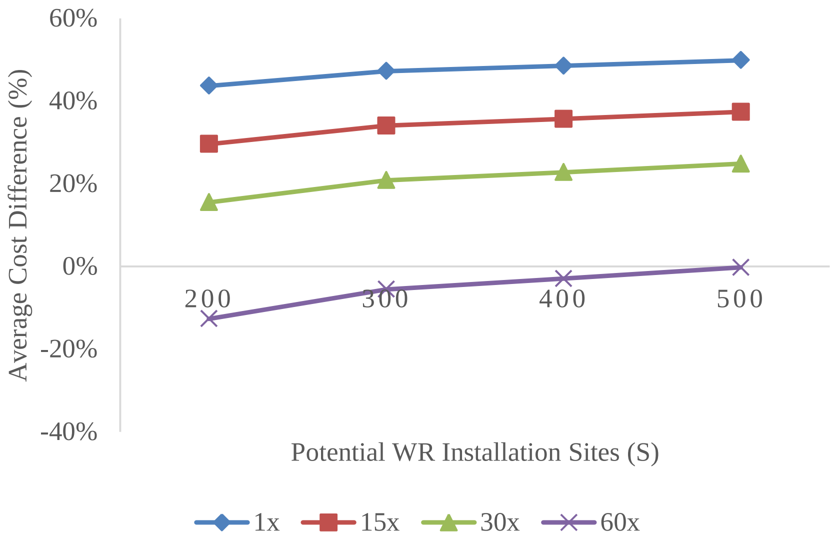


Figure 5.13: Average Percentage Cost Difference between FSN and APN.

5.5 Implications of results

As grid power failure is the major cause of network failures particularly in remote areas and least developed countries, it is essential that backup power be installed to ensure network survivability. The analysis has shown that by providing backup power to a network which has at least one alternative path for each node, the average network cost at the front end can be reduced by up to 34% without affecting the network survivability significantly. The algorithm formulated is also able to assist the potential operators to assess the optimum backup power cost to be chosen.

CHAPTER 6

CONCLUSION

6.1 Concluding Remarks

The Gross Domestic Product growth of a nation is consistently link to the extend of the broadband deployment. It is thus urgent to provide broadband connection to half the world population of 8 billion so as to elevate them from poverty. Optical fibre and wireless communication technology are most feasible to deploy the broadband. While optical communication technology is able to satisfy the need for high bandwidth it is undaunted by its high deployment cost and required a long period to deploy. It is also unable to provide the mobility which is becoming the trend for communication and internet access. The mobility can be easily address by the wireless communication technology which has a much shorter set up time and lower deployment cost as little or no civil work is necessary. It is thus appropriate to form a hybrid optical and wireless broad band access network using the fibre network at the back end and wireless network at the front end. This hybrid system will provide a feasible communication network to lower the deployment cost while providing Gbps transmission rate between the up and down link.

Much work have been done on the reduction or optimisation of network cost while maximising the network capacity. The reduction in deployment cost of the optical segment is often achieved by optimising the length of the fibre required. The effort can easily achieved in a green field deployment. The optimisation effort will be very challenging for a brown field deployment where paths are blocked by existing physical structure. The capacity of the optical network can be improved by having additional fibre or deploying dynamic bandwidth allocation using the time division multiple access in the uplink. Dense Wavelength Division Multiple access where end users are given dedicated wavelength for each end user at the expense of doubling the ONU required. The unlicensed WiFi band is deployed in the wireless segment in order to reduce the cost of deployment. The cost reduction is done by optimising the number of wireless devices required to provide the coverage by using different network topology. The capacity is optimised by using multiple radio channels, routing and channel assignment strategies.

The survivability of HOWBAN where the network is able to maintain its performance in the presence of failures in the network is ubiquitously achieved using redundant components or backup power. Much work have been done on optimising the use of redundant components in either the optical or wireless segment. This research work is different in that it is able to identify the most critical segment where redundancy should be prioritised by using FMEA technique.

The results obtained that priority should be given to provide redundant backup power to the wireless devices particularly in the lease developed countries where 31% or 4 billion of the unconnected world population are residing.

The impact of the deployment of the redundant backup power was investigated using Mixed Integer Linear Programming model and simulate using IBM CPLEX software. The analysis has shown that by providing backup power to a network which has at least one alternative path for each node, the average network cost at the front end can be reduced by up to 34% without affecting the network survivability significantly compared to full survivability network with no backup power. The algorithm formulated is also able to assist the potential operators to assess the optimum backup power cost to be chosen.

International/Government agencies and investors can use the research findings as a reference to evaluate various types of backup power sources for HOWBAN deployment. The findings are particularly relevant in effort to hasten the connection of 31% of the 4 billion world population residing in the LDCs by 2030 so as to heave the deprived community from the anguish of poverty.

It is envisaged that 125 billion IoT devices will be connected by 2030. These devices are enablers for successful deployment of smart and sustainable cities and 4th Industrial Revolution. The research methodology used can be adapted to study the reliability of these networks of IoT devices.

6.2 Future Work

The benefits of broadband access as a driver for achieving the desired sustainable development goals for the well being of the human race is crystal clear but the high investment in launching the communication network still remained a huge obstacle that have stalled the spread of the network to the much needed community. More efforts and researches are required to mitigate the exorbitant deployment cost while providing good quality of service in terms of network capacity, connectivity and survivability so as to attract the more investments.

Two prong approach can be taken in order to address the issues. One of the approach is to improve the efficiency and reduce the power requirement of the hardware. More innovative use of the spectrum to improve the network performance particularly from the regulatory perspective to resolve the communication at the remote areas needs to evaluated. Evaluation can be done on the possibility of opening up more licenced free spectrum for the rural communities. More work can be done on software defined radio and cognitive radio system so as to reduce the cost to accommodate this flexibility in using the spectrum.

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APPENDIX A

CLONAL SELECTION BASED ALGORITHM

Heuristic algorithm will fit in situation where exact algorithm required excessive time to deal with large data sets in complicated optimisation problem. Heuristic programming gives a very good approximate solution but not the exact solution within acceptable duration and computing resources (Dinger, 1988; Kokash, 2005). This approach is able to prevent the algorithm to lock in a local optimum solution. Genetic algorithm is one of the popular heuristic used in optimising WMN (Dinger, 1988; Hermawanto, 2013). The process typically starts with choosing a random set of possible solutions called chromosomes. The set of chromosomes is called the initial population. Selection of the chromosomes is based on a fitness scores. The next generation is generated by combining and mutating the selected chromosomes. The process is repeated until the number of generation and the rate of combination or crossover and mutations set are reached. The constraints of the problem are taken into considerations by applying a penalty function to the fitness function, which breach the constraints. The next section gives an example on the application of clonal selection based algorithm to optimise the assignment of radio channels in a wireless mesh network.

A clonal selection based algorithm can be used to implement channel assignment with minimum interference for Wireless Mesh Network deploying multi-radio. A wireless mesh network that deployed multi-radio will be able to offer more radio channels to increase its capacity to support the clients. As the radio signal in WMN are typically broadcast isotropically, co-channle interference will occur if the channels are not appropriately assigned. The co-channel interference will result in data loss. In Wi-Fi, the co-channel interference is avoided using CSMA-CD multiple access technique. This strategy will degrade the network performance with increase in the number of users due to constant collisions and backoffs. The availibility of non-overlapping channels in Wi-Fi reduce the occurrence of co-channel interferemce thus improving the network performance. The limited number of non-overlapping channel (3 in 802.11n and 12 in 802.11b) will however still put a cap on the size of the increase of mobile clients.

Equipping each wireless router with more radio interfaces, which are tuned to different channel, is also able to increase the network capacity. The limited channels have thus to be allocated or assigned strategically in order to provide maximum coverage and network capacity. The number of channels that can be assigned to a router is constrained by the number of radio interfaces in the routers. This assignment problem with constrained is NP hard (Subramanian et al., 2008). A simple channel assignment is shown in Figure C.1.

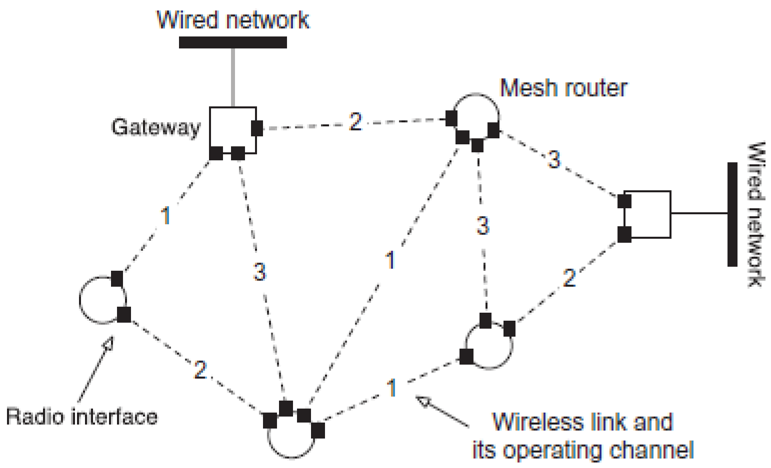

Figure A.1 A multi-radio wireless mesh network with channel assignment.

By assigning channel permanently to radios in WMN will be wasteful on the available channel usage. To improve on the efficiency in using the channels, they can be assigned using the dynamic or quasi-static approach (Subramanian et al., 2008).). In the dynamic approach (Ren and Qiu, 2009), the interfaces at each node are required to switch channels between successive packets transmitted. A node with single interface that switches the channels dynamically will be able to increase its capacity by virtue of the availability of additional channels for transmission. The fast switching time in terms of microseconds in the dynamic approach will require the use of special hardware. It is not feasible to be deployed using off the shelf hardware which require channel switching time in order of milliseconds (Subramanian et al., 2008). In the quasi-static approach, the channels are assigned statically. The static assignment can be changed to accommodate significant changes in traffic or network topology (Tang et al., 2005). The less frequent changes required in switching the channel will allow off the shelf hardware to be used.

An optimisation tool often used for assigning the channel is artificial immune algorithms. An immune algorithm makes use of a simple greedy channel assignment procedure to evolve and improve solutions obtained. The evolution can be done using CLONALG (de Castro and Von Zuben, 2002), a popular clonal selection based algorithm. The clonal selection based algorithms evolve a population of individuals, typically called B-cells, to cope successfully with antigens representing locations of unknown optima of a given function. At each generation, each B-cell in the population is subject to a series of procedures consisting cloning, affinity maturation, metadynamics and possibly aging (collectively known as clonal selection and expansion). An example of the use of clonal selection based algorithm to minimise the interference in assigning radio channels for a multi-radio wireless mesh network is explained next.

The problem involves optimising the quasi-static channel assignment centrally at channel assignment server (CAS) using information on the connectivity and interference between the routers. The routers are assumed to run some link-aware routing protocols (Draves et al., 2004) to overcome short-term fluctuations in wireless link quality. The computed channel assignment will then be disseminated to the routers for making the necessary changes. The information compiled will be used to calculate a low interference channel assignment.

The location of the CAS has no direct influence on the channel assignment performance, but has impact on the amount of control overhead introduced to the network. It is assumed that the CAS is co-located with the gateway node, which is typically strategically placed in the network. As the gateway node needs to perform routine per-packet processing, the processing and memory requirement of a channel assignment algorithm needs to be as small as possible. A wireless mesh network may have multiple gateways. It is assumed that one of the gateways is assigned as the CAS. For large networks (e.g. with size in the order of hundreds), the network can be clustered such that each cluster is served by one CAS. Hence, the description here focuses on channel assignment for nodes within a cluster.

The backbone structure and client access are assumed to use two different radio standards that operate on two distinct central frequencies as is commonly practiced. The 5 GHz Wi-Fi band such as IEEE 802.11-a/n is used for the backbone structure and IEEE 802.11-b/g which operates at 2.4 GHz band is used for the client access. Since the frequencies are far apart, their transmissions are unlikely to interfere with each other. Hence, this description only focuses on the channel assignment for mesh routers forming the backbone structure.

The scenario considered is a wireless mesh network with stationary mesh routers arbitrarily distributed on a plane. Each router is equipped with one or multiple radio interfaces based on IEEE 802.11 standards. As in Marina and Das (2005), all radio interfaces are assumed to use omni-directional antennas and have identical transmission ranges (denoted by R). The connectivity between the routers (nodes) is modelled using an undirected graph, *G(V,E)* where *V* denotes the set of nodes and *E* denotes the set of connectivity links in the network. A connectivity link (*i, j*) marks that the nodes *i* and *j* are within each other's communication range. Henceforth, G is referred to as connectivity graph. In order for two nodes of a link $(i, j) \in E$ to actually communicate, both nodes must have one of their respective radio interfaces tuned to a common channel.

Due to the broadcast nature of the wireless medium, transmissions by nodes that are within each other's interference range may interfere and this results in data loss. The interference between the transmissions is typically represented using an interference model, which defines how transmission over a wireless link can interfere with other links in the network. Various interference models exist in the literature, most notably the physical and the protocol interference models (Guptar and Kumar, 2000) that are described in path loss model (Section 2.3.1.1). The conflict graph (Jain et al., 2003) is used to represent interference between the links. Thus, the discussion is independent of any specific interference model as long as the interference model is defined on pairs of links.

For ease of exposition, a binary interference model (Subramanian et al., 2008) in which two links either interfere or do not interfere is assumed. Given an interference model, a conflict graph can be used to represent the interference between the links. A conflict graph is defined by first creating a set of vertices V_c corresponding to the links in the connectivity graph, i.e. $V_c = \{l_{ij} \,|(i, j) \in E\}$. Next, an edge is placed between two vertices (say, l_{ij} and l_{pq}) in the conflict graph if the corresponding links ((*i*, *j*) and (*p*, *q*)) interfere with each other. The weight of the edge indicates the extent of interference between those links, which depends on the amount of traffic transmission over the links. For simplicity, all nodes are considered to have equal traffic load, hence all links have unity weight. The conflict graph is represented as $G_c(V_c, E_c)$ where E_c denotes the set of edges as defined above. The conflict graph can be used to represent any interference model. As in Marina and Das (2005), the terms "node" and "link" are associated with connectivity graphs, and the terms "vertex" and "edge" are for conflict graphs.

The concept of connectivity graph and interference graph are illustrated in Figure C.2. Each node has a communication range and interference range of R and R', respectively as shown in Figure C.2(a). Figure C.2(b) depicts 5 wireless nodes spaced equally on a plane. The resultant connectivity graph and interference graph are shown in Figure C.2 (b) and (c) respectively. In Figure C.2(c), the conflict graph has four vertices each representing a link in the network. It is assumed that the nodes use IEEE802.11 reliable unicast where nodes access to link is control by the Request-To-Send/Clear-To-Send (RTS/CTS) control frames. Due to this, a transmission on link (*a*, *b*) interferes with the link (*b*, *c*) and (*c*, *d*) but not with (*d*, *e*), thus gives the conflict graph in Figure C.2 (c).

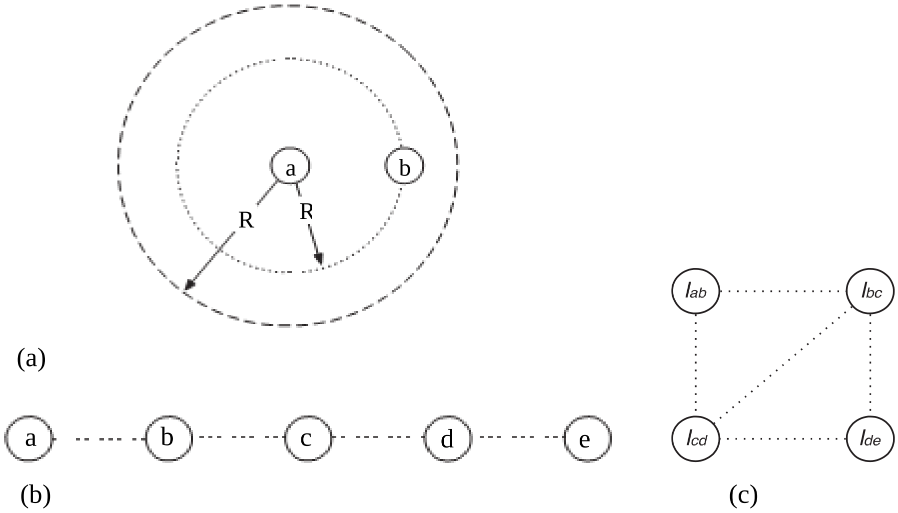

Figure A.2: Concept of connectivity graph and interference graph.

(a) Illustration of communication range and interference range.

(b) Connectivity graph. (c) The corresponding conflict graph.

The channel assignment problem as defined in Subramanian et al. (2008) is adopted here. The goal of the problem is to bind a unique channel to each link in the connectivity graph such that the number of different channels assigned to the links incident on any node is at most the number of interfaces on the node. The optimisation objective is to minimise the total network interference, which is defined as the number of pairs of links that are interfering. This can be calculated from the conflict graph as the number of edges connecting two vertices (representing the links) which are assigned a same channel. Supposing that links (*a*, *b*), (*b*, *c*) and (*c*, *d*) in Figure C.2 (b) are assigned channel 1 and link (*d*, *e*) is on channel 2. This assignment produce a total network interference of 3 due to the interference created by the first three links.

Consider a wireless mesh network represented by connectivity graph $G(V,E)$ and conflict graph $G_c(V_c, E_c)$. Let K = {1, 2, ..., K} be the set of K channels in the system and R_i be the number of radio interfaces on node $i \in V$. Formally, the channel assignment problem is to compute a function $f : V_c \rightarrow K$ to minimise the overall network interference $I(f)$:

$$\text{Minimise } I(f) = |\{(u, v) \in E_c \mid f(u) = f(v)\}| \qquad \text{(C.1)}$$

subject to the below interface constraint,

$$\forall i \in V, |\{ k \mid f(e) = k \text{ for some } e \in E(i)\}| \leq R_i \qquad \text{(C.2)}$$

If the assignment of channels to vertices is viewed as colouring of vertices and recall that vertices (V_c) represent links (E) in the connectivity graph G, the problem can be viewed as colouring of links in G. Unfortunately, standard edge-colouring formulation fails to capture the interface constraint. As the number of edges incidents on a node may exceed the number of interfaces at the node, existing solutions for the problem are not directly applicable here. The example in Marina and Das (2005) is used here to illustrate how the interface constraint may limit the colouring choices. Figure C.3 shows a 4-node connectivity graph with one interface per node. Suppose that there are 2 colours in the system: 1 and 2 which are assigned to link (a, b) and link (c, d), respectively. This occupies the only interface available at the nodes, and results in nodes a and b are disconnected from nodes c and d. In order to preserve network connectivity, only one colour (either 1 or 2) should be used in this example. The term "colour" in place of "channel" for ease of exposition.

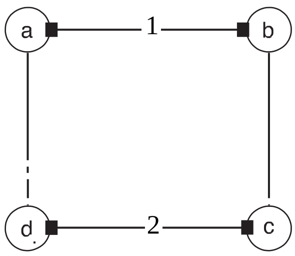

Figure A.3 Example illustrating how arbitrarily chosen colours can break the connectivity. Adapted from Marina and Das (2005).

Subramanian et al. (2008) proposed a Tabu-based algorithm, a centralized and a distributed greedy algorithms for the problem. The algorithms operate on the conflict graph. The Tabu algorithm consists of two phases. In the first phase, the Tabu search based technique (Hertz and de Werra, 1987) developed for graph colouring problem is applied to find a good solution without subject to the interface constraints. Consequently, the solution obtained may violate the interface constraints. This is remedied in the second phase in which a "merge" operation is applied on nodes wherein the interface constraints are violated.

The algorithm used here has a similar structure to this algorithm: the first phase in which immune algorithm is applied to find good solution, which may contain interface constraints violation, and a second phase that repairs the solution. In the first phase, a greedy decision in colouring the vertices is devised to enforce the interface constraints and each violation is given a penalty. This will reduce the number of repair operations in second phase that generally increase the interference of the solution. This is remedied in the second phase in which a "merge" operation is applied on nodes wherein the interface constraints are violated. The repair mechanism is similar to Hertz and de Werra (1987).

In the problem formulation, channels are assigned to conflict vertices (i.e. connectivity links) thus, connectivity is ensured. The genetic algorithm's solution for the problem can be obtained by first choosing those individuals with maximum connectivity and follow by selecting the individual with minimum interference out of these individuals.

The channel assignment algorithm consists of two phases. In the first phase, one of the immune algorithms is applied to find a good solution that may contain interface constraints violation. The solution is then repaired in the second phase.

Phase One

In general, phase one consist of the following basic steps:

1. *Initialization*: create an initial random population of individuals (B-cells), *P*

2. *Main loop*: $\forall x \in P$, do:

(a) *Affinity evaluation*

(b) *Clonal selection and expansion:*

– *Cloning*

– *Affinity maturation*

– *Aging*

– *Metadynamics*

3. *Local search*

4. *Cycle*: repeat Step 2 until a stopping criterion is met.

At the initialization stage, the existence of antibodies (individuals or B-cells) represent the set of candidate solutions. Each B-cell is defined as a vector of integers of finite length $L = |V_c|$, representing the permutations of vertices in the conflict graph *Gc*. The initial population is randomly created. Let P represent the B-cells in the current population and N represent the size of the population.

The affinity for a given solution is defined as the fractional network interference,

$$I_{frac} = \frac{I(f)}{|E_c|} \quad \text{(C.3)}$$

where I(f) is the network interference defined in Equation (C.1) and $|E_c|$ is the total number of edges in the conflict graph. This represents the number of conflicts that remain after channel assignment, as compared to the number of conflicts in the single-channel network.

The affinity for a given B-cell is calculated by first translating the vertex ordering into channel assignment, using a simple greedy assignment strategy. The algorithm visits and assigns channels to vertices one by one in the order presented in the B-cell receptor. The channel assignment is done such that a given vertex v is assigned a channel c that is found to introduce the least increase in the interference to v and the neighbours of v. In addition, the chosen channel must obey the interface constraint on v.

It is interesting to point out that the greedy channel selection procedure may not always result in a valid channel, c. Figure C.4 illustrates a sample visiting order that leads to this problem. For ease of exposition, the visiting order of links in the connectivity graph is given in the figure as the numbers over the links. Suppose that K=4 and all nodes have two radio interfaces. It can be seen that a different channel can be assigned to each of the links (a, b), (b, c), (d, e), and (d, f), as the corresponding nodes have unused interfaces during the visit. By the time link (b, d) is visited, both b and d have used up all their respective interfaces. Because no common channel exists between the nodes, no channel can be assigned to the link. This problem affects the calculation of affinity (see Equations (C.1) and (C.3) for a given solution. In order to account for this, a penalty value is introduced as a measure of interference. The penalty value is set as the number of neighbours of v, i.e., the worst case scenario where the assigned channels interfere with all existing neighbours.

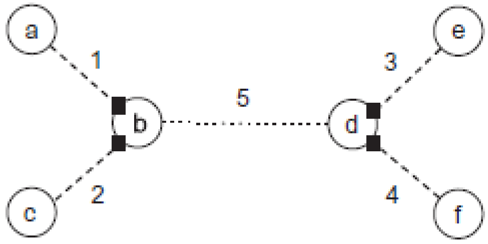

Figure A.4 Sample scenario where a valid channel cannot be found for link (b, d).

In Clonal selection and expansion step, all B-cells in the current population P are subject to all or some of the following operations:

– Cloning. Each B-cell in P is cloned multiple times to produce a clone population.

– Affinity maturation. Each of the clones undergoes a hypermutation process.

– Aging. In this operation, all B-cells exceeding a maximum age will be deleted from the population. The age of a B-cell is increased at each generation.

– Metadynamics. This models the ability of the immune system in continuous production and recruitment of novel structures. Typically, some randomly generated B-cells are added to the population.

The purpose of the local search operation that follows is to improve a given B-cell *x* produced by the clonal selection and expansion procedure for a maximum of I_{tabu} iterations. In general, any local search method may be used. A simple local search based on the widely used Tabu search (Glover and Laguna, 1997) is commonly used.

Like any local search method, Tabu search relies on a definition of neighbourhood. In this example, a neighbour for a B-cell *x* is generated by swapping any two elements of *x*. Starting with the given B-cell, the Tabu search procedure proceeds iteratively to visit a series of locally best B-cells following the neighbourhood. At each iteration, N_{tabu} neighbours are generated randomly for the current B-cell (say *x*) and the best neighbour is chosen to replace *x*, even if the former does not improve the current one. In order to prevent the search from getting trapped in cycling or local optima, a memory structure called Tabu list is used. The list keeps all visited B-cells, and these B-cells are forbidden from being revisited during the next T_{tabu} iterations. T_{tabu} is called the Tabu tenure.

As the local search operation increases the computational needs of the algorithm, the operation is applied only to the population's best B-cell at each generation. The B-cell obtained from the operation will replace the original B-cell if it has a better affinity value.

Phase one is stopped after a predefined number of generations. The best solution obtained is presented to phase two. The details of Steps 1, 2 and 3 in Phase Two is discussed below.

Recall that the solution returned by the first phase (immune algorithm) may violate interface constraints. In phase two, the interface violations are eliminated by applying a "merge" procedure adopted from Subramanian et al. (2008) on each unassigned conflict vertex.

Let i and j denote the underlying nodes for link represented by a conflict vertex in question. The merge operation randomly picks one of the two nodes to work on. Suppose that node i is chosen. The objective is to reduce the number of channels assigned to i by one so that a new channel can be assigned to link (i, j). To begin with, two channels c_1 and c_2 incident on i are picked. Following that all links with c_1 will be changed to c_2. To prevent such a change from creating interface constraint violations at other nodes, the merging of c_1 to c_2 is recursively applied to all links that are "connected" to the links whose channel has been just changed from c_1 to c_2. Here, two links are deemed to be connected if they are incident on a common node. Essentially, the propagation of the merging process ensures that for any node j, either all or none of the links incident on j with c_1 are changed to c_2. It is clear that at the completion of one merge procedure, the number of distinct channels incident on i and other nodes is reduced by at most one, and no new channel is introduced. Thus, repeated application of the procedure is guaranteed to resolve all interface constraints. At the end of the procedure, a channel c_3 from j is selected for use by link (i, j). In the worst case, a complete merge operation may visit all nodes and their incident links, thus has a complexity of $O(|V||E|)$.

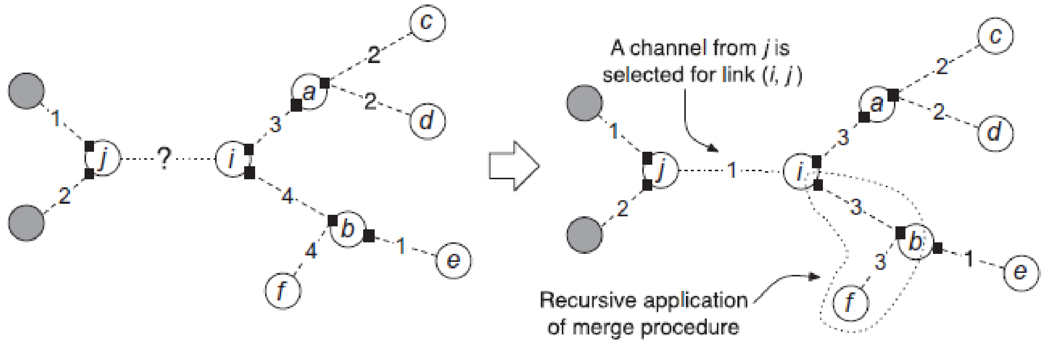

Figure A.5 Sample topology before and after a merge operation.

Since a merge operation may result in increase in network interference, channels c_1, c_2 and c_3 are selected for the merge procedure such that they give the least increase in the network interference due to a complete merge operation. Figure C.5 shows the channels assignment of a sample topology before and after the merge operation. In the example, $c_1 = 4$, $c_2 = 3$ and $c_3 = 1$.

APPENDIX B

SURVEY ON SIMULATION TOOLS

The availability of free commercial and open source simulation and optimising tools have encourage much research work on wireless mesh network. Among the areas that attract attention of those involved in wireless communication network are topology and spectrum optimisation. This section looks at the optimisation tools available and how researchers in the area of wireless mesh network deploy them.

Open source and commercial solvers are typically used to simulate or solve the optimisation models. Among the solvers that are commonly used are CPLEX, OPNET, Qualnet, ns-2 and J-Sim. The first three are commercial tools while the rest are open source.

1. IBM-ILOG CPLEX

CPLEX is IBM optimising software that is widely used in the commercial sector. Engineers commonly adopt this solver for evaluating performance of telecommunication networks. Academic and students can access the software by a simple registration process. The operating systems that are being supported include AIX, HP, Linux, Mac, Solaris and Windows. Optimisation on Linear Programming (LP) and Mixed Integer Programming (MIP) are included. The MIP features also allows three heuristic mode including callback heuristic, solution improvement heuristic and Relaxation Induced Neighbourhood Search (RINS) heuristic. Extensive online user and support documentation is readily available on the IBM website. Full version of the software is available for students and academic involved in research. Some examples of work done using CPLEX are described next.

In Correia et al. (2009), CPLEX was used to investigate a fault tolerant hybrid optical wireless mesh network by making efficient reuse of the spectrum available. The aim was to maximise the scalability of the network to handle increasing traffic demand thus ensuring survivability of the network.

The use of cognitive radio in fair bandwidth allocation to radio channels in a wireless mesh network was studied in J Tang et al. (2010). Linear programming based optical and heuristic algorithm was used to investigate the feasibility. The simulation was done using CPLEX. The evaluation of system was done under eight different scenarios group into two categories. A transmission range of 250 m is selected for all the channels in the first categories. The transmission rates used in the first category are 11, 36 and 54Mbps. A square topology of 1300 m x 1300 m was selected as the test site where the nodes were placed. Three groups of channels are also used in the second category. The transmission range of the 11 Mbps group is 500m. The 36 Mbps group has a range of 250 m while 100 m range is used for the 54 Mbps group. Second category has a square topology of 2500 m x 2500 m.

In Lee et al. (2011) CPLEX was used to evaluate the effect of node failures in a hybrid wireless optical communication network on the deployment cost and survivability. Study was done based on IEEE802.11 standard devices. Wireless transmission rates set at 54, 48, 36, 24, 12, and 6 Mbps for a transmission radius of 50, 80, 100, 150, 200, 250m. Communication ranges for backhaul links are 500m and the maximum optical transmission rate of 1.25Gbps was selected. The test field is a 2 km 2km with the Optical Line Terminal located at the center. The study was done using Mixed Integer Linear Programming (MILP).

2. Riverbed Application and Network Performance Management Solutions (OPNET)

OPNET (Optimised Network Engineering Tools) is a product of OPNET Technologies, Inc. OPNET deals with evaluation of network performance. The company was acquired by Riverbed in 2012 and the product is incorporated in Riverbed application and network performance management solutions. It has good GUI interface. The operating system supported includes various version of Windows operating system including Windows XP and Vista. Online support document are available only to registered clients. A modeller university programme, which offers free access to the product, is available for the research academic and students from qualified universities. Some examples of work done using OPNET are described next.

OPNET was used in Iraqi (2011) to study the effect of a square, triangle, and hexagon network topologies on the traffic that can be handled by the network. The work also includes ways to determine adding of new gateway as the demand for the network capacity grows.

Jun and Sichitiu (2003) studied problem of fitting a wireless mesh network with exact capacity by using the bottleneck collision domain concept. The results obtained were simulated using OPNET modeler for verification. MAC layer, 802.11b with RTS/CTS were chosen as it is well modeled in OPNET

In Kim et al. (2009), OPNET was used to evaluate the characteristics and demand estimation of the network traffic in WiMAX mobile communication system. The evaluation was also done on the performance of VoIP and TCP/IP in WiMAX network.

3. QualNet

QuelNet is one of the products of Scalable-networks technology. Other products supported are EXata and Scenario Player. It offers Scenario-Based Communications Simulation for network based systems. QualNet is composed of the following components: QualNet Architect QualNet Analyser QualNet Packet Tracer QualNet File Editor and QualNet Command Line Interface. It can work on 32 and 64 bit systems from both Microsoft Windows and Linux platform. Under its EDU Program Research License and EDU Program

Teaching License, university students and faculty at accredited educational institutions are eligible to gain free access the commercial tools and supports resources for the purpose of teaching and research in the science and application of communications simulation. The licenses are valid for a period of 1 year. Participants of the programme are required to share the model library created and their experience on using the tools. Papers published using results generated from the tools are promoted on the company website. Some examples of work done using Qualnet are described next.

A joint routing scheduling scheme ensuring robust performance under traffic information uncertainty was investigated using Qualnet in Wang et al. (2009). The scheme is able to avoid the re-calculation and re-distribution of the routing and scheduling if the traffic load changes is within the stipulated range. 802.11 b Physical layer modelling and upper layer protocol was implemented using Qualnet. The simulation was done at 11 Mbps with the same transmission power for all the nodes.

4. Network Simulator 2 (ns2)

ns2 is a free open source software that is widely used by the academics involving in network research. It is a discrete event simulator used for researchers involving in study of networking. Though extensive online documentation by developer but is not so friendly to unskilled NS users. The programme is written using C++ and OTcl (Tcl script language with Object-oriented extensions developed at MIT). A C++ compiler is required in order to install ns-2. It is designed for Unix (FreeBSD, Linux, SunOS, Solaris) but may also work under Windows platform. It is designed for Unix (FreeBSD, Linux, SunOS, Solaris) but may also work under Windows platform. Some examples of work done using ns-2 are described next.

In Mohsenian and Wong (2007) metaheuristic algorithm was used to investigate four important factors related to multi-channel wireless mesh network (MC-WMN). The factors include determination of set of logical links and their assignment to wireless router, allocation of channel to the logical links and the routing of the packets. The simulation was performed on using ns-2 The network test site is 1000 m x 800 m with User Datagram Protocol and Transmission Control Protocol traffic at 54 Mbps. Each of the ten WMN samples generated has 30 routers each with 3 NICs. Four routers are assigned as gateways and located at each corner of the test site.

ns-2 was also used in Ding et al. (2013) to evaluate the advantages of using hybrid channel allocation in a wireless mesh network. The hybrid approach includes a combination of static and dynamic channel allocation. An interface in dynamic channel allocation is allowed to change channel frequency while it is not permitted in the static approach. Simulation was performed at 11 Mbps data rate. The interference range is 500 m that is double that of the transmission range. 50 nodes is placed randomly is a square topology of 1200 m^2.

5. J-SIM

JSim is an open source Java-based discrete event simulator of an M/M/s queue system developed entirely in Java^{TM}. This network modelling and simulation tool is targeted at students and educators who may use it to investigate network operations. J-Sim has facility for modifying the queuing systems thus enabling larger and application specific simulation to be performed. JSim can be installed Linux, Macintosh and Windows platform and can run as an applet within web browser. Some examples of work done using J-Sim are described next.

In Chowdhury and Akyildiz (2008) the authors applied the feature of the ability of cognitive radio to sense and change frequency spectrum to enable radios to intelligently locate and use frequencies other than those in the 2.4GHz ISM band and improve problem of traffic congestion and limited spectrum to support a large number of closely placed nodes in a wireless mesh network. Simulation was done using J-Sim. The mesh radio transmits isotropically with a radius of 150 meters over a square topology 900 m x 900 m.

6. OTHERS

Other optimisation tools include ns-3 and OMNeT++ , MATLAB and Advanced Interactive Multidimensional Modelling System (AIMMS). ns-3 and OMNet++ are free open source tools that are widespread acceptance in wireless mesh network. MATLAB is a commercial tool and it does not provide free access for student and academics.

AIMMS is a commercial package that is popularly used in supply chain, energy and utility and oil and gas sectors has not been used widely in the telecommunication especially the hybrid wireless and optical communication network. Free student and academic license are offered by AIMMS and may be able to attract it to be adopted by researchers in the area of wireless network communication. The free student license does not required registration but the size of the optimisation models is limited to 300x300. The student license is equipped with the sufficient solvers for mixed integer programming, nonlinear programming, mixed integer nonlinear programming, mixed complementarity programming, global optimisation and Robust Optimisation. With the free academic license, researchers are offered unrestricted access and full features including all the solvers equipped in AIMMS. The free license has a validity of one year and is restricted for non-commercial work only. Optimisation solutions created with AIMMS can be used either as a standalone desktop application or can be embedded as a software component in other applications.

PUBLICATIONS

Journal Papers

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