Power Minimization and Optimum ONU Placements in Integrated Wireless Optical Access Networks

By

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Abstract

The deployment of optical fibre in place of copper cable in access networks has experienced remarkable growth over the past several years due to a wide range of benefits. A major benefit of optical fibre over copper cable is that it is more secure and immune to electromagnetic interferences. Optical fibre has also provided the capability of handling higher throughputs for longer distances, and experiences no crosstalk between other fibre optic cables. However, the last mile reach to end-users with optical fibre is very costly. This alternative replacement results in increased costs for manual labour and energy consumption in the access network. The current demand in all areas of telecommunications, and especially access networks, is greener networking. In order to offset the high costs of optical access implementations and to satisfy this demand, an investigation into integrated wireless optical access networks (IWOAN) is warranted.

The proliferation of wireless devices has also motivated the interest in IWOAN as it combines the flexibility and efficiency of wireless with the security and stability provided by optical. With the emergence of smart phones and tablets, wireless access networks are now supporting an increasing amount of traffic volume with improved throughput and accessibility. We employ a Passive Optical Network (PON) infrastructure from the central office to the customer, traced from the Optical Line Terminal (OLT) to the customer premises devices known as Optical Network Units (ONUs) for IWOAN. At the ONU, the optical fibre is terminated and wireless communication is implemented. The ONU acts as a wireless access point/gateway for wireless Base Stations (BS) serving different coverage areas in point-to-point topology. With recent trends of advanced wireless technologies, premium rich applications such as multimedia streaming, interactive gaming and cloud computing are delivered in a satisfactory and economic way. This wireless-optical integration aims to reduce and solve the cost of replacing copper cables. However, another issue is raised with increased costs in energy consumption due to the integration of wireless and optical communication. Typically a large number of ONUs need to be deployed in order to serve many wireless BSs located in different coverage areas. As a result, any cost savings gained by the integration process is exhausted with the increased cost of power consumption.

Energy efficiency is a vital issue to solve. The trade-off for reducing the cost of optical implementations is increased cost of energy consumption. Hence, this thesis proposes an optimized approach to IWOAN through the means of power minimization. We formulate an algorithm that will design the network layout for optimum placements of ONUs to support the BS demands, while minimizing power consumption. We have developed two formulations to measure minimum power consumption. Initially we formulate power consumption on the foundation of aggregate uplink traffic rates at the ONU and the distance for transmission between an ONU and its BSs. We then modify this formulation as a function of uplink traffic rates at the ONU, exclusively. By modeling two formulations we achieve an important observation; the total power consumption is primarily dependent on the transmission power and less on traffic power. We have developed several in-house simulation programs of the network using CPLEX optimization studio. We evaluate our original formulation, and then evaluate the modified formulation and compare results to obtain various power components. We obtain three power components: start-up power, and two dynamic powers; traffic power and transmission power, which all summate to our minimum power consumption. Constraints are used to create an ideal network with system limitations and acceptability. These include channel assignment, ONU installation, network capacity and signal quality.

Our in-house simulation program measures several effects on power consumption: effects of initial placements of ONUs; ONU transmission distances; increase in the total number of BSs in the network, and; channel reuse method using cell structures. In all scenarios we map out optimum placements of ONUs, determine the minimum number of active ONUs, and the minimum power consumption.

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D	Chanel Reuse Distance
R	Radius
N	Number of Cells per Cluster
K	Channel Reuse Factor
C/I	Carrier to Interference ratio
γ	Environmental Factor
P_d	Dynamic Power (nJ/bit/m)
$P_{d'}$	Dynamic Power (nJ/bit)
W	Watts (nJ/sec)
B	Set of fixed locations for BSs
O	Set of possible locations for ONUs
W	Set of available wireless channels per ONUs
C	Number of channels needed to support uplink traffic
A	Upper bound on number of channels per ONU (i.e. $C \leq A$)
R_i	Transmission distance of BS_i
T_k	Transmission distance of ONU_k
J'	Upper bound of J_k
λ_i	Uplink traffic rate of BS_i
I	Maximum acceptable interference
G	An arbitrarily large number
P	Bootstrap power (start up power)
β	Power coefficient (nJ/bit/m)
α	Power coefficient (nJ/bit)
D_{ik}	Distance from BS_i to ONU_k
$D_{ii'}$	Distance from BS_i to $BS_{i'}$
U_k	Binary variable denoting if ONU_k is installed

G_{ik}	Binary variable denoting if ONU_k is connected to BS_i
X_{ji}	Binary variable denoting if channel j is assigned to BS_i
Y_k	Binary variable denoting if ONU_k is active
J_k	Capacity of ONU_k
$I_{ii'}$	Co-channel interference of $BS_{i'}$ on BS_i

List of Abbreviations

3GPP	3G Partnership Project
AMC	Adaptive Modulation and Coding
BS	Base Station
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CO	Central Office
CRM	Channel Reuse Method
DSL	Digital Subscriber Line
EDRB	Energy Distance Ratio per Bit
eNB	Enhanced Node B
EPON	Ethernet PON
FDD	Frequency Division Duplex
FSO	Free Space Optical
FTTB	Fibre to the Building
FTTC	Fibre to the Curb
FTTH	Fibre to the Home
FTTN	Fibre to the Node
FTTx	Fibre to the x
GPON	Gigabit PON
GSM	Global System for Mobile Communications
HC	Hill Climbing
HFC	Hybrid Fibre Coax
IEEE	Institute of Electrical and Electronic Engineers
IMT	International Mobile Telecommunications
IP	Internet Protocol
ISP	Internet Service Provider

ITU-R	International Telecommunication Union Radio Communication-Sector
ITU-T	International Telecommunication Union Telecommunication-Standardization Sector
IWOAN	Integrated Wireless Optical Access Network
LAN	Local Area Network
LOS	Line-of-Sight
LTE	Long Term Evolution
m	meter
MAN	Metropolitan Area Network
Mbps	Megabits Per Second
MIMO	Multiple-Input Multiple-Output
MME	Mobility Management Entity
NGPON	Next Generation PON
NIU	Network Interface Unit
nJ	nanoJewels
NLOS	Non-Line-of-Sight
nm	nanometer
OADM	Optical Add-Drop Multiplexer
OECD	Organisation for Economic Co-operation and Development
OFDMA	Orthogonal Frequency Division Multiple Access
OLT	Optical Line Terminal
ONU	Optical Network Unit
P2MP	Point to Multipoint
P2P	Point to Point
PAN	Personal Area Network
PON	Passive Optical Network
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying

REL-10	Release 10
RF	Radio Frequency
RFoG	Radio Frequency over Glass
RN	Remote Node
SA	Simulated Annealing
SAE	System Architecture Evolved
SC-FDMA	Single Carrier Frequency Division Multiple Access
SFNet	San Francisco Network
SS	Subscriber Station
TDD	Time Division Duplex
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TPC	Transmission Power Control
UE	User Equipment
UMTS	Universal Mobile Telecommunication Systems
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WMN	Wireless Mesh Network

Chapter 1

Introduction

1.1 Motivation of Research

There is a long-standing interest in green networking in the telecommunication industry as energy costs continue to increase for the foreseeable future. According to A. Gladisch *et al.* current power consumption of the global network is about 2.4%. This percentage could increase to over 4% as the access rates increase. The highest power consumption has been found in access networks, data centres and mobile access networks (Figure 1.1)[1]. With real-time bandwidth-heavy applications in smart devices (phones/tablets) and the recent trend of high level traffic in cloud computing, access networks will be required to support and maintain the increasing demands. By 2015, prices for 80% of cloud services are projected to include a global energy surcharge due to these rising energy costs [2]. Under the Copenhagen Accord, Canada aims to have a reduction of 17% in green house gases from 2005 levels by 2020 [3]. Thus, a shift toward energy efficient green networks, also referred to as greening of the network, will be very beneficial. With the use of optical access as an alternative to traditional copper access networks, higher bandwidth and traffic levels can also be supported.

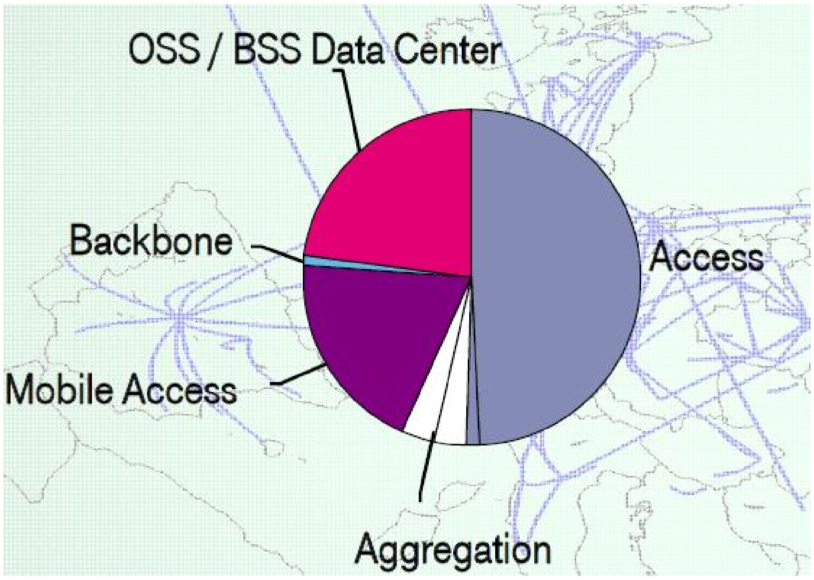

Figure 1.1: Power consumption of the internet

A major benefit of optical fibre is its security and immunity to electromagnetic interference in comparison to copper coaxial cables. Although the benefits are high, there is an increased cost of optical access implementation over what is called the last mile effort. The last mile effort refers to the manual labour required to install the optical network including, but not limited to, civil work, ducts and cables. The rerouting of road traffic and local business accessibility is also affected due to the laying of optical fibre. In order to offset the cost of optical access implementations, an investigation into integrated wireless optical access networks (IWOAN) is warranted.

The proliferation of wireless devices has also motivated interest in IWOAN as it combines the flexibility and efficiency of wireless with the security and stability provided by optical. With the emergence of smart phones and tablets, wireless access networks are now supporting an increasing amount of traffic volume with improved throughput and accessibility via implementations such as: Long Term Evolution (LTE), LTE-Advanced, WiMAX and Wi-Fi. Currently, wireless communication using LTE-Advanced (LTE REL-10) meets and surpasses the International Mobile Telecommunications (IMT)-Advanced requirements of peak data rates of up to 1 Gbps in the downlink, and 500 Mbps in the uplink [5]. The network performance of the implementations largely depends on proper deployment of equipment, as this is critical to energy efficiency.

Research has been conducted in network placement algorithms where network performance largely depends on the placement of optical network units (ONUs)/gateways where the optical and wireless parts meet [4]. The majority of this research considers cost effective solutions for distance, signal strength, signal propagation, and traffic. In our work, we design a placement algorithm considering cost effective solutions in developing energy efficiency in IWOAN to further improve network greening. Our use of optical and wireless access allow us to achieve the best of both worlds, as the signal path that travels on optical fibre does not require any active elements. The only elements used are passive splitters, couplers, and combiners. As a result, the optical back-end is very robust. The wireless front-end is flexible in comparison to wired connections, such that the reach is extended to locations not accessible by wire.

The optical back-end of IWOAN is developed using a Passive Optical Network (PON), communicating in a point-to-multipoint (P2MP) manner. In P2MP a single ONU can communicate with multiple base stations (BSs) via downlink, or multiple BSs can communicate to a single ONU (multipoint-to-point) via uplink. PON defines the central office as the location of the internet service provider (ISP), whom provides one wavelength channel for downlink and another wavelength channel for uplink. The central office hosts the optical line terminal (OLT), which coordinates the multiplexing of optical signals to the various ONUs. Between the OLT and ONU, optical fibre and passive components (splitters, combiners, and couplers) are deployed. These ONUs are located at various locations dependent on the network the PON is developed for, as shown in Figure 1.2. Multiple connection methods of fibre-to-the-x (FTTx) have been used in practice for PON: fibre to the node (FTTN), fibre to the building (FTTB), fibre to the curb (FTTC), and fibre to the home (FTTH). These methods have been widely deployed ever since 2004, when the International Telecommunication Union Telecommunication Standardization Sector (ITU-T) completed the recommendations defining Gigabit-PON systems [6].

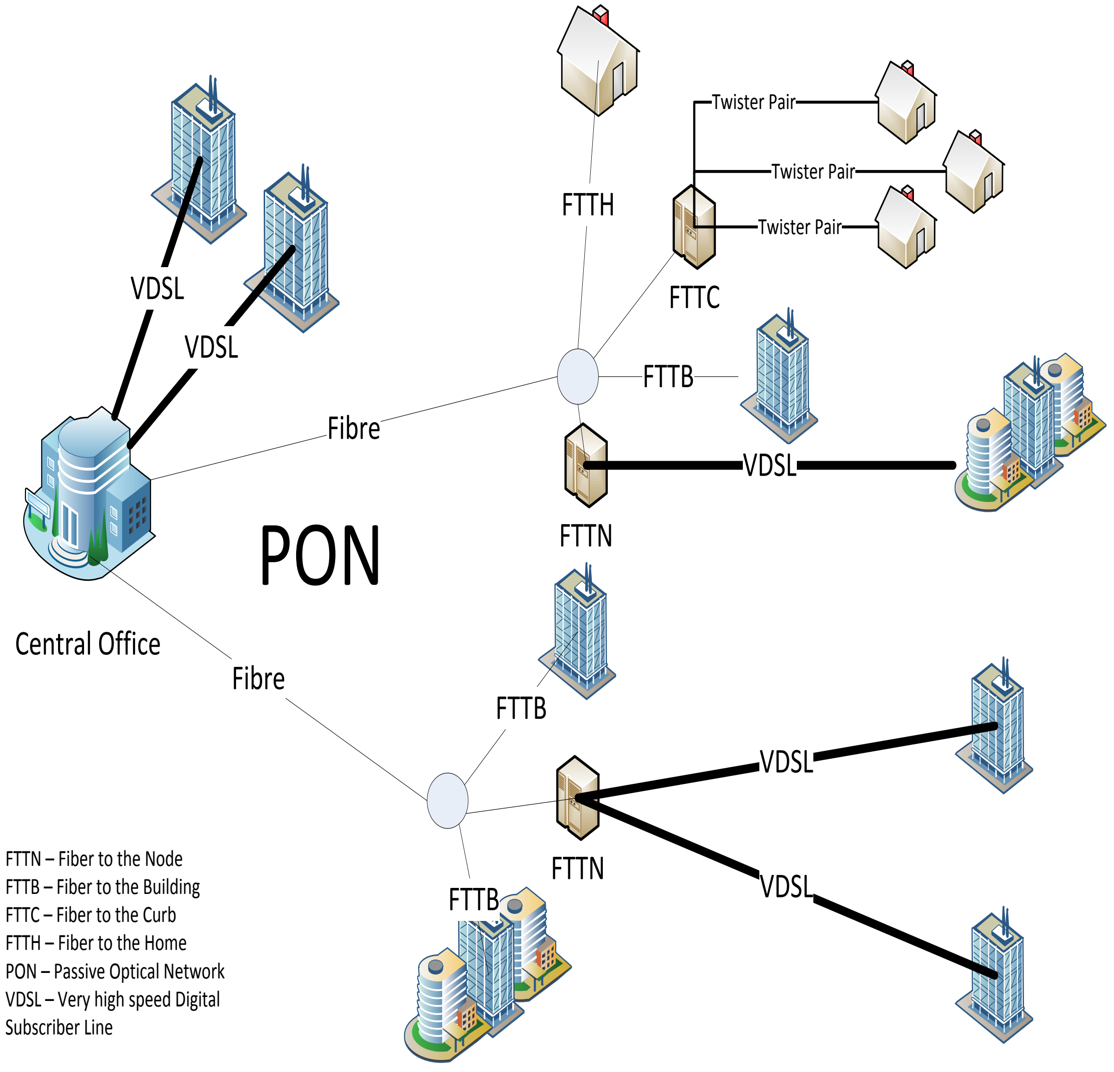

Figure 1.2: PON network (FTTx)

A PON can modulate in single wavelengths using time division multiplexing (TDM) or work with multiple wavelengths using wavelength division multiplexing (WDM). Due to increased bandwidth, heavy services and increased number of users, the ITU-T has already defined Next Generation PON (NGPON) to offer low costs, large capacity, wide coverage, full service, and interoperability with existing technology [6]. WDM is emerging as a leading multiplexing scheme to meet the standards for NGPON, receiving much attention due to its ability to support multiple wavelengths.

As the wireless front-end of IWOAN is developed dependent on the ISPs implementation plan, any wireless technology can be employed. With recent tremendous growth in the wireless network industry, bandwidth and user demands can be met. As an alternative to optical fibre, cable and DSL, we are interested in wireless access technologies addressing the last-mile communication link. While being cost competitive these technologies must offer broadband wireless access and support fixed, portable and mobile operations for voice, video and data services. The three major wireless technologies (i.e. Wi-Fi, WiMAX, and LTE) all have their own advantages and disadvantages. Our work results are independent of any specific wireless technologies. The parameters, constraints, and formulation do not use specific detail of individual wireless technologies. The work is developed as an overall solution for wireless-optical communication.

1.2 Objectives and Contribution

With network power consumption becoming an increasingly vital issue, optimizing power consumption of a wireless optical access network for uplink and downlink traffic is a challenging task. The focus of this thesis is to minimize the power consumption for uplink transmission of the ONU such that channel assignment, ONU installation, network capacity, and signal quality constraints are met. For future research minimization of power consumption for downlink transmission can be implemented from the foundation of our work, further discussed in the system model and development.

We make three important contributions to the evolving study of IWOAN

1) We design an algorithm that will output optimum placement locations for ONUs.
2) We formulate two models, first we minimize power consumption in terms of energy consumed per bit per meter transmitted.
3) Second we minimize power consumption in terms of energy consumed per bit.

The results from the contributions allow us to determine the power consumption is more heavily dependent on the transmission distance, and less dependent on traffic rates. Figure 1.3 displays our model for IWOAN and the flow of uplink traffic from BSs to ONUs wirelessly, and from ONUs to OLT wired.

1.2.1 Placement of ONUs

Our formulation for minimum power consumption provides several results, one of which is determining the best possible locations to place ONUs. The efficient deployment of the least number of ONUs will largely affect the network performance and energy efficiency. The point at which the optical and wireless ends meet between BSs and ONUs determines the minimum power consumption. Thus, placement of ONUs is a key contribution of this thesis.

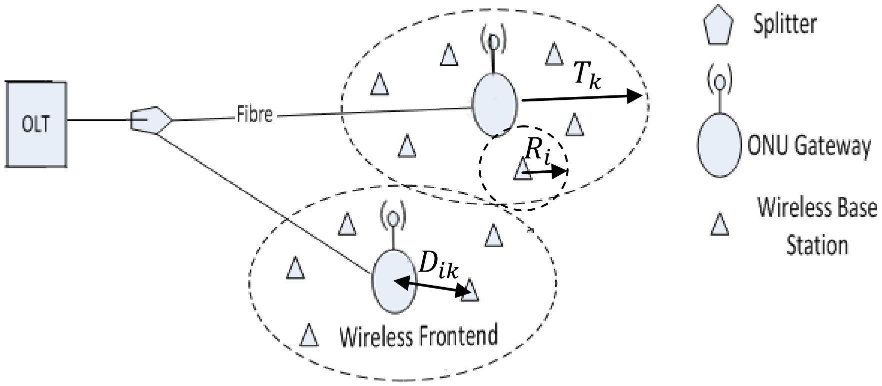

Figure 1.3: Uplink traffic flow for IWOAN

1.2.2 Minimization of Traffic and Transmission Power

We formulate a model that includes two major components of power consumption: traffic and transmission. Our formulation consists of two variable components: start up power and dynamic power. The start up power also known as bootstrap power is a constant determined by datasheets of the ONU used. Essentially bootstrap power is the power required to start up the internal components of an ONU. The dynamic power component present during equipment operation is modeled by the following, for every meter of transmission the ONU consumes an amount of energy per bit [7, 8]. The dynamic power is a function of both the traffic power and transmission distance power. Traffic power is essentially the traffic load at the ONU, recognized as the uplink access rate from BSs. In a realistic network, the power is dependent on heavy or low traffic load conditions at the main operating unit (i.e. ONU). The transmission distance power is a function of the distance between the BSs and the ONU. In wireless networks, the power will increase or decrease based on the distance from the receiver and transmitter.

1.2.3 Minimization of Traffic Power

In order to distinguish the effect of traffic power and transmission distance power, we formulate a modified formulation to solely depend on traffic power as the dynamic power component. The dynamic power is measured in terms of energy consumed for every bit of traffic [7]. By doing this we are able to obtain the individual dynamic power components, the traffic power and a relatively close approximation of the transmission distance power. As a result, we conclude that the power consumption is more dependent on transmission distance power and less on traffic power. Although our results depict exact values, it is a rough approximation due to network dynamics changes from the original formulation to the modified formulation.

We assess the minimization of the formulations using an in-house simulation implemented using mixed integer linear programming on CPLEX Optimization Studio. Our formulation is linear, with mixed integer decision variables, and linear and quadratic conditions to maintain our constraints.

1.3 Thesis Outline

The rest of this thesis is organized as follows in Chapter 2, we will focus on theoretical background and literature review needed to grasp the understanding of IWOAN. We provide background information on passive optical networks, wireless networks, and the joint contribution of the two. We also exploit the disadvantages and advantages of these technologies. Finally, we look at other placement algorithms taken for wireless optical access and their goals. Following the theoretical background, Chapter 3 will discuss the system model and development of our methods for IWOAN. Chapter 4 details the mathematical formulation, inputs, parameters and constraints used to develop our simulation results. In Chapter 5, we provide a detailed description of our simulation setup and the San Francisco network that we run our simulations for. Chapter 6 details and analyzes the simulation results. In Chapter 7, we conclude with a thesis summary and provide recommendation for future work in IWOAN.

Chapter 2

Theoretical Background

In this chapter we investigate Optical Access Networks, more specifically Passive Optical Networks, Ethernet over Fibre, Radio Frequency PON, and Free Space Optical Networks. We also discuss Wireless Access Networks such as, Wi-Fi (Wireless Fidelity), WiMAX (Worldwide interoperability for Microwave Access) and LTE (Long Term Evolution). The integration of wireless optical access is also discussed, in preparation for the system model and development in Chapter 3. We will also describe placement algorithms, energy efficiency and the goal toward green networks.

2.1 Optical Access Networks

The transmission of network traffic was originally developed on copper wiring and Ethernet access networks. This transmission method, although faster than the 56 kbps dial-up line, was unable to provide the required bandwidth for today's rich applications [9]. Traditional copper access has various limitations such as repeaters that must be used for large transmission distances, resulting in data loss, poor signal quality, and increased power consumption. The replacement solution to copper access limitations and increased bandwidth demands is optical access networks. More so, PON is the best current solution for high speed access networks.

2.1.1 Optical Fibre Broadband Network Access

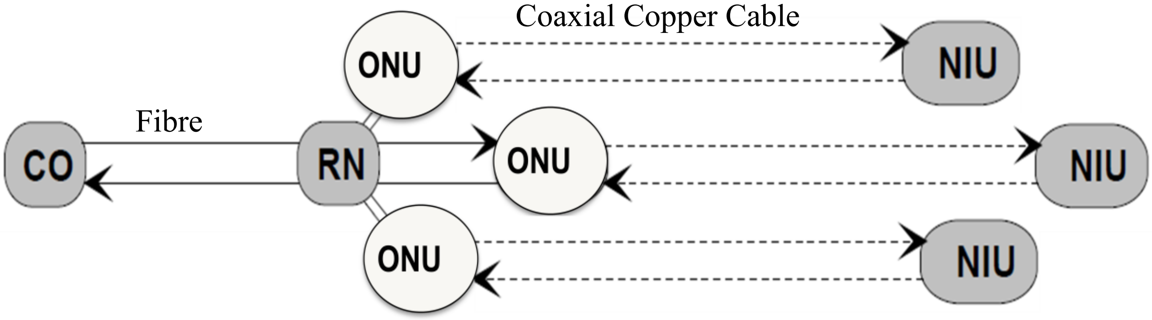

Figure 2.1: Optical access network components

Fibre access systems, commonly referred to as Fibre-To-The-x (FTTx) are what constitute PON architecture. They are primarily used for last-mile connection from the central office (CO) of the ISP to the end-user. Several implementations of FTTx exist, and four major ones are fibre to the node (FTTN), fibre to the building (FTTB), fibre to the curb (FTTC), and fibre to the home (FTTH). These implementations all function by the use of OLTs, remote nodes (RN), ONUs, and network interface units (NIU). Figure 2.1 displays the order of connections for optical access components.

The OLT coordinates multiplexing between various ONUs that are transmitting/receiving data. The RN is a simple passive device that processes data and broadcasts it to the entire set of ONUs. The ONU transforms the incoming optical signals into electronic signals to be transmitted to the end-user. The NIU is the device that serves as the switching point between the ONU to the wiring of end-user's premises. In Figure 2.2, FTTx networks are displayed. In FTTN the optical fibre is terminated at the ONU, typically a street cabinet a large distance away from the end-user (>300 m). From the remote node, copper coaxial cable connections are to be implemented to each user. FTTN is used commonly to deliver triple-play telecommunication, a term used for delivery of cable internet, television and telephone in a point-to-point (P2P) manner. In P2P systems, each end-user receives their own coaxial cable. In FTTC, fibre is extended to the ONU at the curb of the end-user (< 300 m away). This network extends fibre closer than FTTN, providing higher levels of bandwidth and less interference for the coaxial cable connected to the end-user. FTTB is very similar to FTTC; the fibre is pushed to the building or basement, with rest of the connection through coaxial cable. Finally, FTTH brings the fibre to the home, where it is terminated outside the wall of the user.

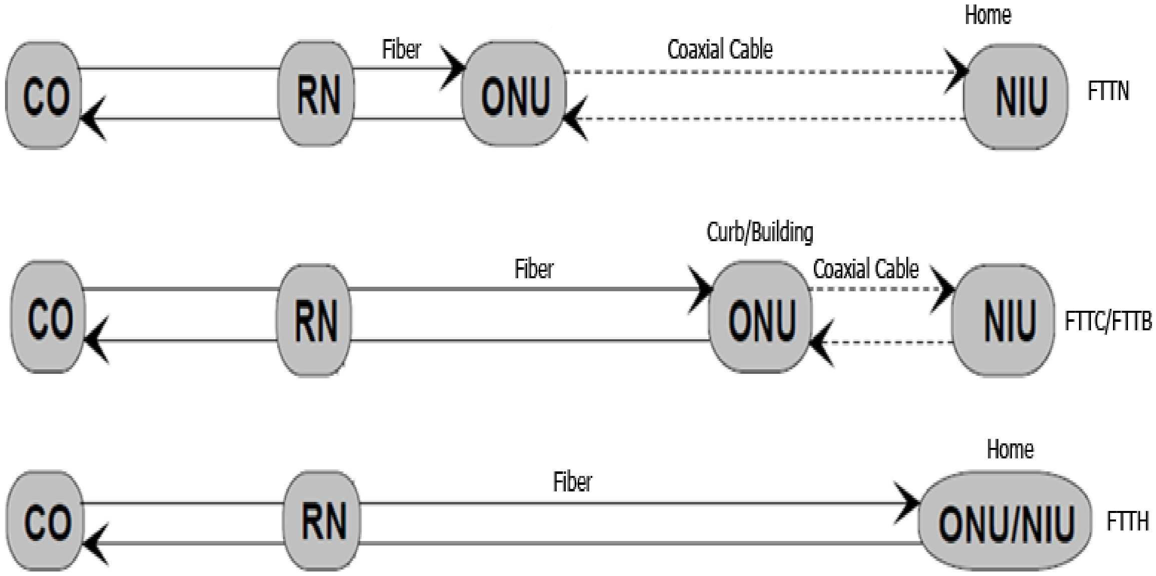

Figure 2.2: FTTx networks

2.1.2 Passive Optical Network

The basic architecture of PON is seen in FTTx networks. The elements used in PON are all passive elements such as the fibre, combiners, splitters, and couplers. These passive elements create the optical distribution network through the optical path, connecting the OLT to the ONU. Typically, most PON architectures follow a FTTC network, as this solution is considered to be more economical than FTTB and FTTH due to the costs of laying fibre [4]. PON employs a P2MP transmission for downlink, while uplink follows a multipoint-to-point transmission. Transmission from OLT to ONU is called downlink (Figure 2.3), while transmission from ONU to OLT is called uplink (Figure 2.4). For uplink, the transmission of multipoint-to-point works by multiple ONUs capable of transmitting to an OLT simultaneously. There are two methods to coordinate the transmission of traffic: TDM, and WDM. These, as well as the advantages of PON as an access network are briefly discussed in Section 2.1.2.1 to 2.1.2.3.

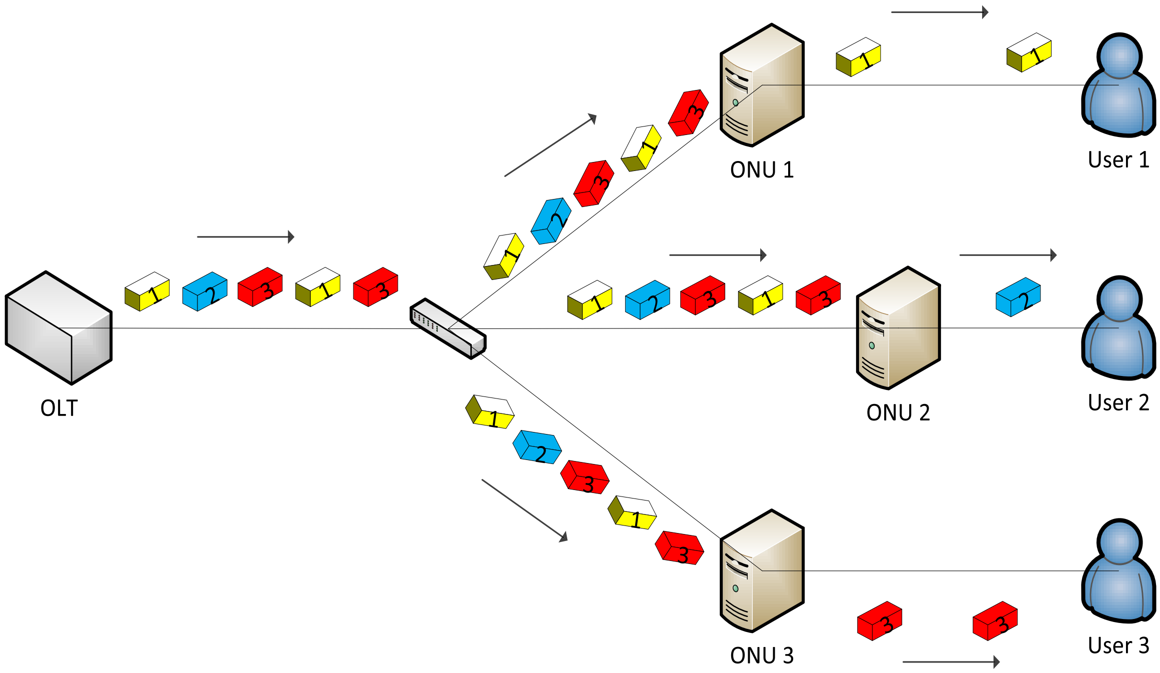

Figure 2.3: Downlink transmission in PON

2.1.2.1 Time Division Multiplexing PON

There are two main methods of transmission in PON. One is the TDM, whereby a multiplexer located at an ONU interleaves several bits of data from the user-end in assigned timeslots. These slots typically interleave from slower access rates into one faster access rate from the ONUs to the OLT. The bandwidth is shared among the end-users A method used commonly, time division multiple access (TDMA) is a type of TDM PON which is incorporated into the shared network. Multiple users share the same wavelength by dividing the signal into different time slots, thus several BSs or ONUs can share the same fibre optic cable, coupled by passive components [10]. Another type of TDM PON is dynamic TDMA. This method uses scheduling algorithms to provide quality of service to users. It improves throughput, latency, fairness, and efficiency of traffic. Dynamic TDMA is used in many applications including broadband radio access networks, WiMAX and Bluetooth. The use of single wavelength PON results in a limitation in bandwidth, thus a better solution is wavelength division multiplexing.

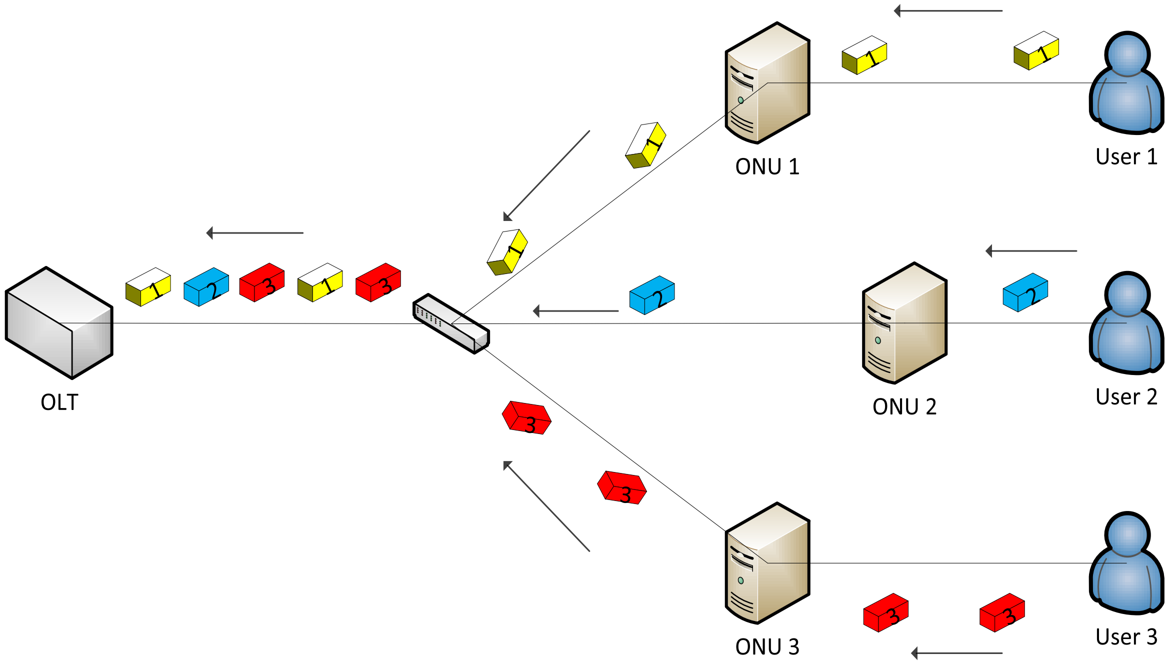

Figure 2.4: Uplink transmission in PON

2.1.2.2 Wavelength Division Multiplexing PON

The second main method of transmission in PON is through WDM in which a multiplexer splits or combines a signal at different wavelengths. In WDM PON each ONU will operate at different optical carrier signals. A multiplexer will combine a number of signals onto a single fibre and transmit it from the various ONUs to the OLT or vice-versa. At the OLT, a demultiplexer is present to split the signals accordingly [10]. A major benefit of WDM is the capability of expanding network capacity without the need to lay more fibre cabling. Shown in Figure 2.5, the optical add-drop multiplexer (OADM) is a device that aids to expand the network by adding one or more new wavelength channels to an existing WDM signal. Moreover, the OADM can also drop (remove) an optical signal if required [11]. Wavelengths can transmit at various band levels; integrated voice, data, and video operate at 1490 nm, 1310 nm, and 1550 nm. ISPs offer all three services to end-users multiplexed over a single fibre using WDM techniques and distributed through passive optical splitters.

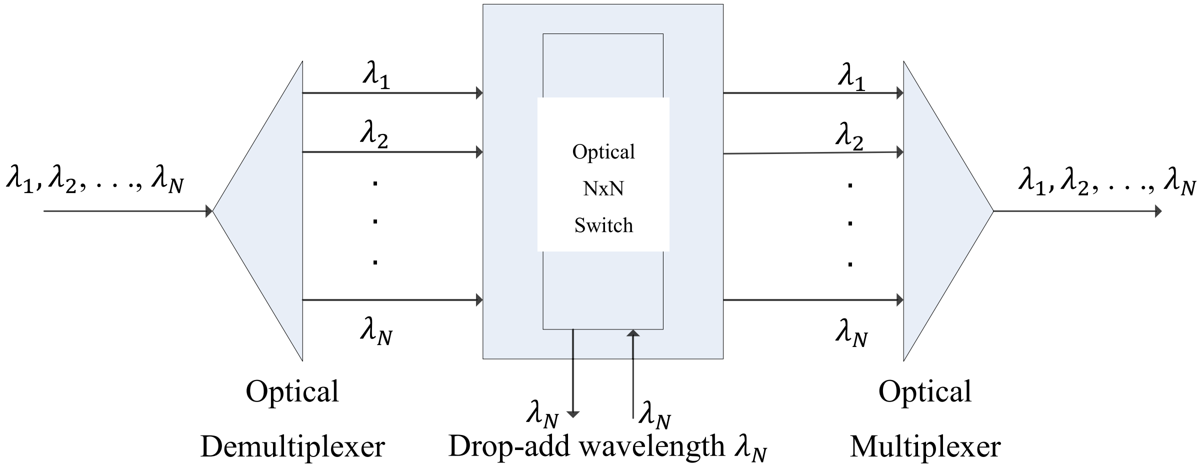

Figure 2.5: Optical add-drop multiplexer

2.1.2.3 Advantages of PON

Currently, there is interest in PON as a dominant access network. This access network offers a wide range of benefits, especially with improvements to GPON and the anticipated implementation of NGPON.

- PON has the capacity for large data over fibre and high-speed traffic rates for applications such as online HD streaming, live broadcasts, stock exchange markets and cloud computing.
- PON can operate for distances of 20 km without the need of amplification. Fibre optics face less interference and line attenuation than coaxial cables.
- The maintenance of PON is significantly less than other access networks as active multiplexers and demultiplexers are not required. In the field, the passive optical components do not require power to operate.
- PON has the capability to adapt to new upgrades and technological advances with minor replacements to hardware and software.

2.1.3 Other Optical Access Networks

There are several other approaches to optical access networks; we are not limited to TDM and WDM PON. Below, we will discuss the methods of Ethernet over fibre and radio frequency PON, as well as a method that is receiving much more attention: free space optical networks.

2.1.3.1 Ethernet Over Fibre

Ethernet over fibre uses standards published by working group IEEE802.3ae that define a data rate of 10Gbit/s for Ethernet full duplex P2P networks [12]. This approach is very costly as it requires a large number of fibres and optical transceivers. Ethernet over fibre has the capability of running on full capacity as a single fibre is used for each end-user. Thus this method is used dominantly for business subscribers. To help reduce costs of fibre deployment, this network can generally be interconnected by Ethernet switches. With the use of single (bidirectional) or dual (unidirectional) fibres, users can be connected to the Ethernet switch directing communication to and from the central office, as shown in Figure 2.6 [12].

2.1.3.2 Radio Frequency PON

Radio frequency (RF) PON also known as RF over Glass (RFoG) is a material upgrade to hybrid fibre coax networks (HFC). HFC is the combination of optical fibre and coaxial cable used in broadband networks deployed by multisystem operators. RFoG is a cost-effective method for cable operators to migrate from HFC to FTTH networks. At the cable service operator's headend a cable modem termination system broadcasts and receives voice, data and video traffic through RF signals. This RF signal is converted into an optical signal that is to be transmitted over glass (fibre) in PON. The optical signal is transmitted through fibre to the fibre optic node, which terminates the optical fibre and converts the signal into delivered traffic to the home network. RFoG PON is a deep fibre network in which the coax portion of HFC is replaced by a single fibre cable, capable of transmitting uplink and downlink. In HFC the backend from the optical node to the service provider is composed of fibre. the front-end uses coaxial cabling. Benefits of RFoG PON over traditional coaxial cabling include an increase in support of 1 GHz in the downlink spectrum, increased bandwidth in uplink traffic and significant cost reductions in network operation and maintenance. RFoG PON uses the passive optical network enabling support for other technologies such as GPON, EPON, and NGPON to coexist in the same network [13].

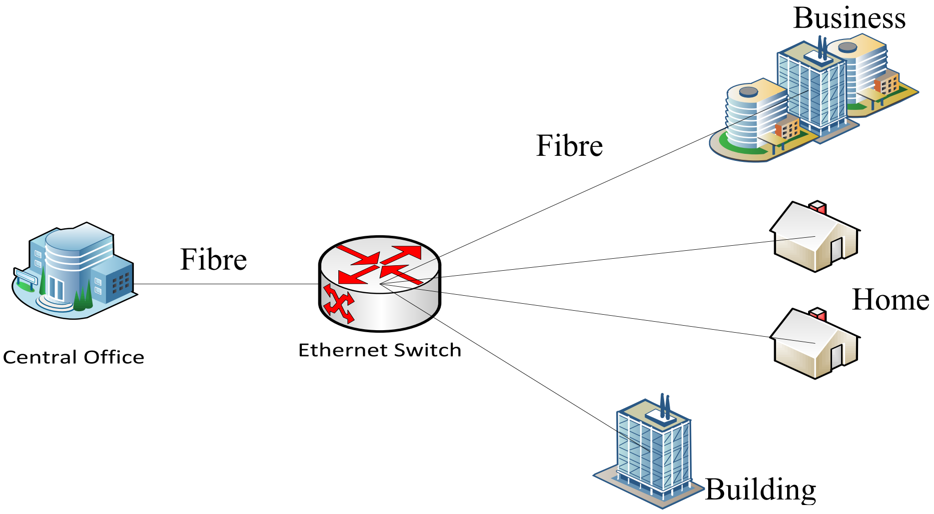

Figure 2.6: Point-to-point Ethernet optical access

2.1.3.3 Free Space Optical Networks

In free space optical networks (FSO), also known as optical wireless communication, the communication of traffic from end-users to the CO are done wirelessly over the atmosphere and through fibre optics. FSO communication is inexpensive, as there is far less optical fibre laying required. In an FSO set up (Figure 2.7), at the front-end the optical transceivers are mounted on top of buildings to propagate light in the atmosphere efficiently. At the backend from the CO to the transceiver or receiver there is a fibre optic connection. These transceivers use telescopes to improve the alignment of optical links to develop a P2P mesh network connecting the user directly to the CO. A disadvantage of FSO is that the atmosphere is not an ideal transmission medium for optical frequencies, as it is dependent on weather conditions. Optical frequencies can lose some of their energy from signal scattering, absorption, and scintillation. Optical signal scattering takes place when light signals are redirected as they pass through water particles. Optical signal absorption occurs when optical energy is converted into heat due to striking particles such as smog. Optical signal scintillation occurs when heated air from chimney stacks or factories cause a bending of the optical beam.

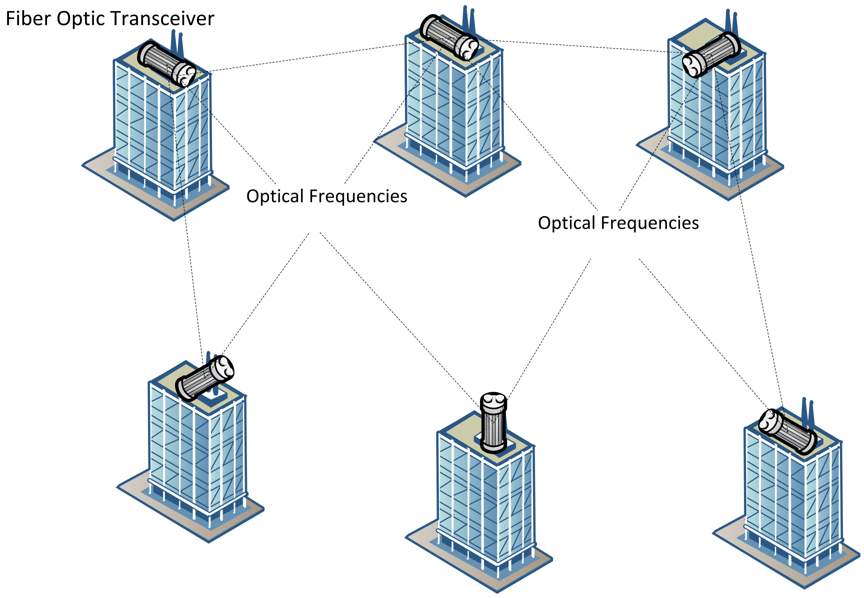

Figure 2.7: Free space optical point-to-point mesh network

In a study by S. Subramaniam Ahdi [14], a wireless mesh network is deployed using FSO links. The emphasis in this network is placed on the network capacity as the major constraint, resulting in the formulation of optimal placement of FSO transceivers. This hybrid RF/FSO network is capable of increasing the available bandwidth for each subscriber with strategically placed FSO transceivers. An integer linear program was developed to obtain optimal solutions, with a proposal for a relaxation to achieve the upper bound on the network capacity. This method of RF/FSO shows significant improvements in the network capacity at a fraction of the entire network upgrading costs. The integration of wired networks such as PON will greatly improve the reliability and survivability of FSO [12]. This integration is investigated in this thesis, as IWOAN.

2.2 Wireless Access Networks

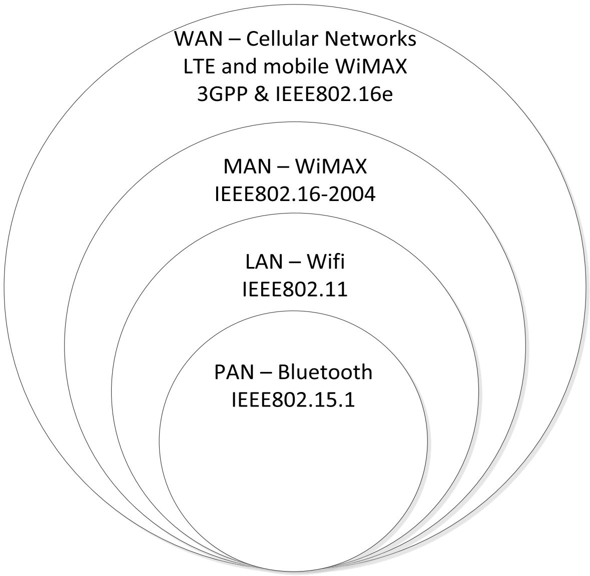

Figure 2.8: Wireless network types

There are a wide range of innovations and methods developed recently for wireless access networks. We will investigate wireless access toward the integration of wireless optical access networks. In this section we provide a brief introduction to the basics of wireless communication. We then focus on recent trends of wireless technologies such as Wi-Fi, WiMAX and LTE. Although wireless access networks cannot compete with wired access networks in terms of data rate and reliability, they do offer flexibility and mobility. A list of wireless technologies is displayed in Figure 2.8.

- WPAN – Wireless Personal Area Network is used for covering a small area among data devices communicating close to one person or themselves. Bluetooth IEEE 802.15.1 and ZigBee IEEE 802.15.4 are WPAN standards, whose coverage area are limited and support low data rates [15].
- WLAN – Wireless Local Area Network is a wireless communication network that allows multiple users to communicate with each other at reasonably high

speeds in comparison to WPAN and cellular networks. IEEE 802.11 standards known as Wi-Fi are currently the most prominent WLAN [16].

- WMAN – Wireless Metropolitan Area Network is a connection of multiple LANs or a group of stationary/mobile users distributed over a large area. WiMAX IEEE 802.16 is an example of WMAN [17]. Wireless infrastructures or optical fibre connections are used to interconnect spread out LANs.
- Cellular Networks (WAN) – Wireless Wide Area Network is a connection of networks covering a relatively large area interconnected by nodes, hosts, or LANs. The internet, cellular networks, mobile WiMAX and LTE are examples of WAN [18].

2.2.1 Wireless Communication Basics

In a basic wireless configuration there are three components: transmitter, wireless channel and receiver. At the transmitter end, the purpose is to encode the data and prepare it into a signal format that can be transmitted over the wireless channel. Figure 2.9 demonstrates how the data travels through the transmitter, completing three required functions: channel coding, modulation, and precoding. The signal then passes through the wireless channel, and will face attenuation due to propagation loss, noise, and interference. Once the signal passes the wireless channel it approaches the receiver end, where the data is recovered through three procedures: equalization, demodulation and channel decoding (Figure 2.9). At the equalization stage, the modulated signal is recovered by removing the carrier signal of the wireless channel. The equalization filter must cancel out any group or phase delays from the original signal due to propagation loss, noise and interference. All frequency components of a signal are delayed when propagating through space or a medium [27]. The modulated symbols are then demodulated to convert the signal to bit format. The channel decoder then recovers the information.

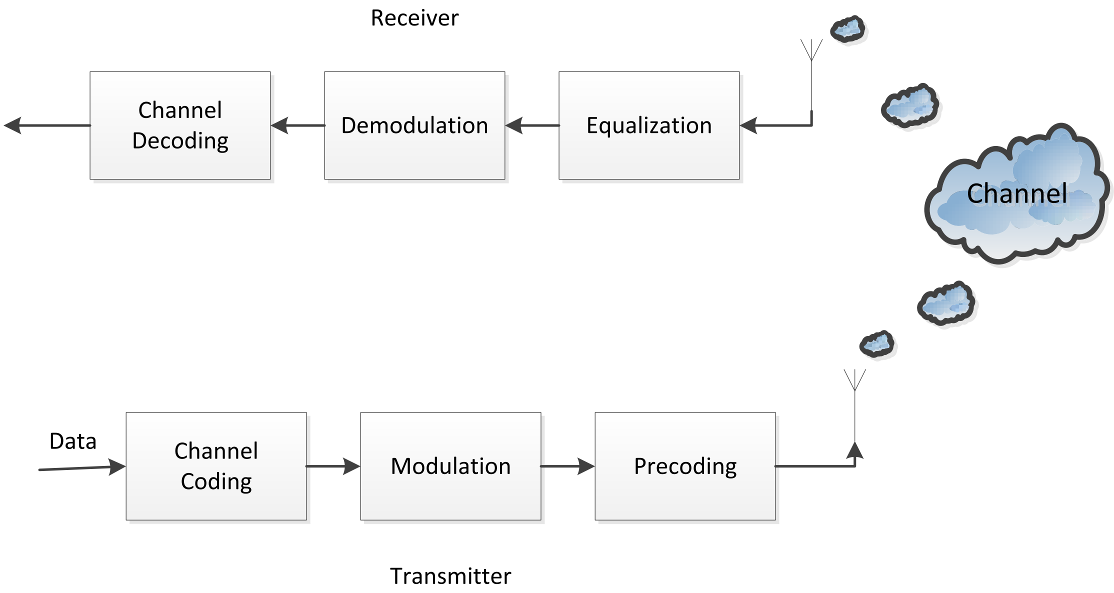

Figure 2.9: Wireless communication block diagram

2.2.2 Wireless Access Technologies

2.2.2.1 Wireless Fidelity (Wi-Fi)

Wi-Fi developed in the 1990s for wireless local area networks on the standards of IEEE 802.11. Wi-Fi networks allow devices that have Wi-Fi technology to exchange data wirelessly through access points. Groups of access points may be joined together to form a large scale mesh network. Due to the benefits of flexibility and low deployment costs, Wi-Fi is being used in homes, businesses, university and college campuses, local street hotspots and city wide Wi-Fi coverage [19]. The advantages of Wi-Fi range from cheap deployment costs of wireless routers to low costs of Wi-Fi electronic devices. Mainly due to mass production of manufacturers developing laptops with built-in wireless network adaptors, therefore increasing the demand and reducing development costs. Locations in which cables cannot be run rely heavily on Wi-Fi and wireless access methods. Typically Wi-Fi networks have limited range, in Table 2.1 a display of 802.11 a/b/g/n/y standard transmission ranges and other useful information such as operating frequency's and maximum data rates are given [12]. IEEE 802.11n-2009 standardization improves upon previous IEEE 802.11 standards by adding multiple-input multiple-output (MIMO) antennas with data rates up to 248 Mb/s and transmission range of 70 meters.

Table 2.1: IEEE standard specifications for 802.11a/b/g/n/y

Parameter	802.11a	802.11b	802.11g	802.11n	802.11y
Operating frequency (GHz)	5	2.4	2.4	2.4 and 5	3.7
Maximum data rate (Mb/s)	54	11	54	248	54
Maximum indoor transmission distance (m)	35	40	40	70	50
Maximum outdoor transmission distance (m)	100	120	120	250	5000

A disadvantage of Wi-Fi is the high power consumption that results from transmission distance between the access point and device, which typically manifests in the battery life of mobile devices. Wi-Fi-Sense was developed to conserve battery power of mobile devices, while improving Wi-Fi usage [20] . Wi-Fi-Sense results show energy savings of up to 79%, resulting in considerable increases in Wi-Fi usage.

2.2.2.2 Worldwide Interoperability for Microwave Access (WiMAX)

The growth of wireless data has surpassed the growth of voice data. According to Cisco's Visual Networking Index, in 2011 the growth of wireless data has more than doubled voice data, and is expected to double again in 2012. In North America alone mobile wireless data traffic grew 171% [21]. The change from circuit switching to packet based and all IP networks has been ongoing since the beginning of the millennium [22]. A wireless access network that has been receiving increasing attention is Worldwide interoperability for Microwave Access (WiMAX). As an alternate to cable and digital describer line (DSL), WiMAX has been developed to deliver connectivity to end-users wirelessly. Standardized by working group of IEEE 802.16, WiMAX provides cost competitive, omnipresent broadband wireless access and high quality of service capabilities. WIMAX is managed and ratified by the WiMAX Forum, a non-profit organization that certifies and promotes the compatibility and interoperability of broadband wireless products based upon IEEE standard 802.16 [23]. The IEEE 802.16 standards are shown in Table 2.2. The original standard 802.16 defines the backhaul P2P connection with bit rates up to 134 Mb/s in the frequency range 10 to 66 GHz. The improvement IEEE 802.16a is defined for P2MP wireless access at bit rates up to 75 Mb/s transmitting at 2 to 11 GHz frequency level. The standardization of IEEE 802.16e is the very basis of Mobile WiMAX due to the support for handovers between BSs [12].

Table 2.2: IEEE standard specifications for 802.16a/e/m

Parameter	802.16	802.16a	802.16e	802.16m
Operating frequency (GHz)	10 - 66	2 - 11	2 - 6	To be determined (TBD)
Maximum data rate (Mb/s)	134	75	15	1000
Typical cell size (km)	2 - 5	7 - 10	2 - 5	Microcell (TBD)

The latest revision to WiMAX, 802.16m meets requirements set for the next generation of global mobile broadband technology (IMT-Advanced) placed by the ITU Radiocommunication Sector (ITU-R). An agreement for IEEE 802.16m Wireless MAN-Advanced (known as WiMAX 2.0) was finalized and endorsed by the ITU member states at the World Radio Communication Conference in 2012 [24]. WiMAX has support for a variety of access schemes such as orthogonal frequency division multiplexing and orthogonal frequency division multiple access. Moreover, as an IP-based wireless technology, WiMAX can be interconnected with other wireless or wired access technologies.

WiMAX has the capability to provide two levels of wireless service, non-line-of-sight (NLOS) and line-of-sight (LOS), as shown in Figure 2.10 [25]. In NLOS, a small antenna on a laptop or computer connects to the tower. Similar to Wi-Fi, WiMAX uses a lower frequency range as lower wavelength transmissions are not easily interrupted by physical obstructions. In LOS a fixed dish antenna points directly at the WiMAX tower from a rooftop or pole creating a stronger more stable signal, thus sending a large amount of data with fewer errors. LOS transmissions use higher frequencies ranging up to 66GHz. At these transmission levels there is less interference and more bandwidth [25].

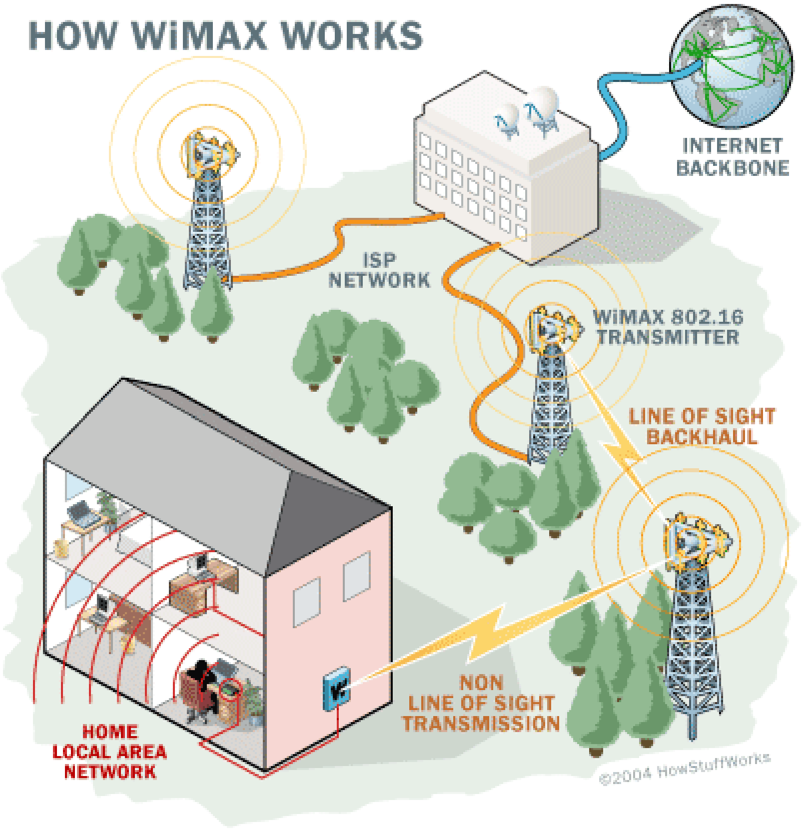

Figure 2.10: How WiMAX works

The broadband wireless access network of WiMAX is delivered between BSs and Subscriber Stations (SS). A subscriber station is a device that connects the user to a WiMAX network. While the BS will be located at predetermined locations by the ISP, the SS will be located at the customer premises. Downlink communication occurs from the BS to SS, and uplink occurs from SS to BS. WiMAX supports bidirectional communication between two devices by methods of time division duplex (TDD) or frequency division duplex (FDD). In TDD, a full duplex communication is initiated over a half duplex communication link. A common carrier signal is switched in time to handle the bidirectional communication of uplink and downlink. In FDD the carrier frequency is different for uplink and downlink. The carrier frequencies are separated by the frequency offset and are efficient for symmetric traffic, allowing full duplex communication. For downlink, WiMAX functions as a point-to-multipoint (P2MP) network. BS broadcasts identical data to all SSs, the SSs then determine which data is intended for it. For uplink, WiMAX functions as a multipoint-to-point network. SSs share the resources of BS. A medium access control mechanism of the BS settles the access between all the SSs through bandwidth allocation schemes and scheduling algorithms. An adaptive power efficient packet scheduling algorithm was developed [26] to provide minimum fair allocation of the channel bandwidth for each packet transmitted, additionally minimizing power consumption. In this algorithm, packets were adaptively transmitted as per allotted slots from different priority of traffic classes, dependent on the channel condition. For example, if the buffer size of the high priority queues with bad channel condition exceeds a threshold, then the priority of those flows would be increased by adjusting the sleep duty cycle of existing low priority traffic, thus preventing starvation.

2.2.2.3 Long Term Evolution (LTE)

Finalized by the ITU in 2008, a major wireless technology receiving attention is Long Term Evolution (LTE). At the World Radio Communication Conference 2012 in Geneva, the ITU’s Radio Communication sector agreed to accept and ratify LTE-

Advanced standards that meet the IMT-advanced requirements [24]. The 3G Partnership Project (3GPP) developed LTE to be an all-internet protocol (all-IP) framework that will function uniformly with previous wireless and wire implementations [27]. An upgrade to legacy wireless technologies such as global system for mobile communications (GSM) and universal mobile telecommunication systems (UMTS), LTE provides data rates of up to 100 Mbps downlink and 50 Mbps uplink. LTE-Advanced is capable of up to 1 Gbps downlink and 500 Mbps uplink. The successor of LTE is LTE-Advanced, an evolution of LTE providing improved performance and service capabilities through high peak data rate and low latency. The network architecture of LTE is simple and sophisticated, as shown in Figure 2.11.

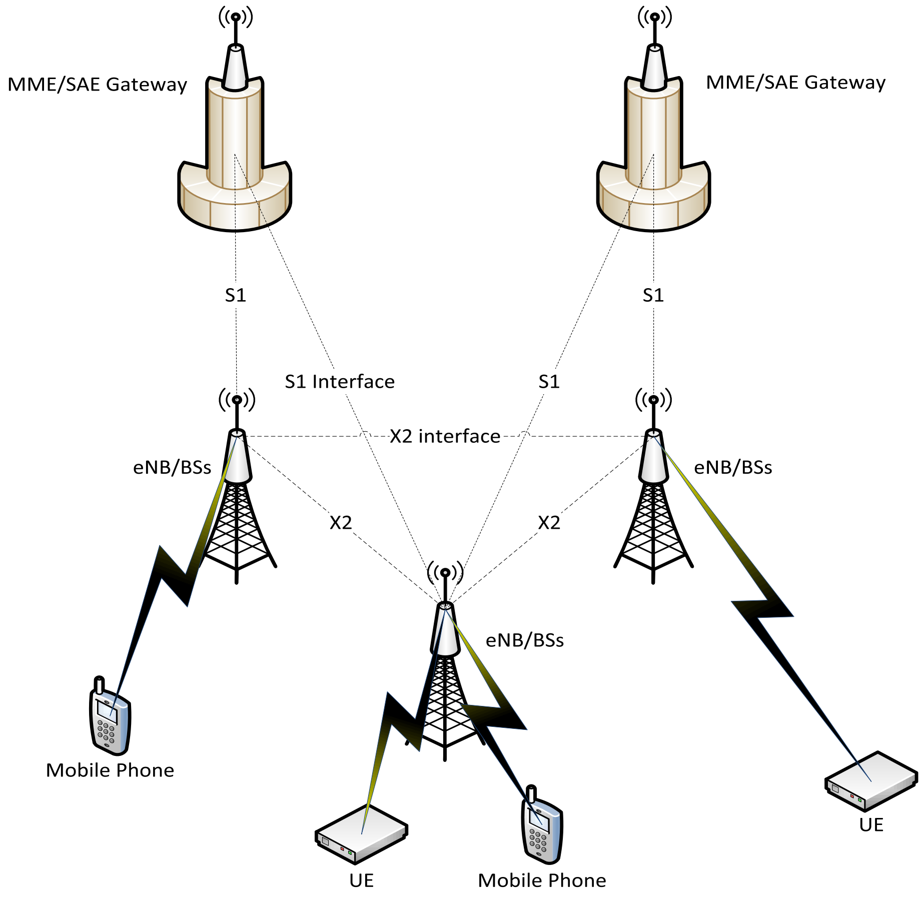

Figure 2.11: Long Term Evolution network structure

Referring to Figure 2.11, the user equipment (UE) or mobile phone is connected to the enhanced node B (eNB) or BS. The eNBs communicate with each other using X2 interface, which is the handover of a mobile UE from one eNB to another. The eNBs also communicate with the mobility management entity (MME) in the control plane, also known as the system architecture evolved (SAE) gateway through S1 interface. In downlink communication, orthogonal frequency division multiple access (OFDMA) is used at the physical layer, while the uplink communication is based on single carrier frequency division multiple access (SC-FDMA). LTE takes advantage in the use of transmission power control (TPC) and adaptive modulation and coding (AMC) [27]. TPC is a mechanism used to reduce the power of a transmitter to the minimum necessary to maintain the link with a certain quality, avoiding interference with other devices and extending battery life. AMC provides the flexibility for each user to match the modulation coding scheme with the average channel condition. During a single frame interval the power of the transmitted signal is held constant, and the modulation and coding format matches the received signal quality or channel condition. For example, higher order modulation (64 QAM, QPSK) and higher code rates are assigned to users closer to the BS, but as the distance from the BS increases the modulation order and code rate will also decrease [28]. Mobility management is a key task of LTE for the purpose of hard handoffs. Soft handoff is used in code division multiple access (CDMA) cellular networks, allowing the user to be connected to several BSs during handoff before being handed off from the source BS to the target BS. Hard handoff before connecting to the target BS breaks off its connection from the source BS. For uplink and downlink separation, LTE supports both TDD and FDD. Furthermore LTE uses adaptive link adaptation, time-frequency scheduling and multiple-input multiple-output (MIMO) technique, which is the use of multiple antennas.

2.3 Integrated Wireless Optical Access Networks (IWOAN)

The Organisation for Economic Co-operation and Development (OECD) reports that on average 16.96% of all households worldwide are covered by FTTH/B [29]. Shown in Figure 2.12, there are about 86.5% of Japanese and 67% of Korean households with access to FTTH/B coverage. Finland, Denmark, the United States, France and Sweden reach an FTTH/B household coverage above 10%. Although the coverage percentage remains low, operators have increased their fibre deployments drastically since 2009 with advancements in passive optical networks. Optical fibre technologies such as FTTH/B are capable of supporting the capacity and reliability of communication for high bandwidth media rich applications, especially with optical fibre deployed all the way to the customer premises. However, this laying of fibre infrastructure to all end-users requires a significant amount of funding. Furthermore, the enormous growth in mobile data traffic rates results in increasing desire by users for untethered access. The need for ubiquitous access is increasing as end-users communicating with mobile devices want to remain connected to the network as they move. Combining wireless access technologies with optical fibre technologies provides this ubiquitous "anytime-anywhere" access network, known as IWOAN. Thus, IWOAN integrates the best of both worlds in wireless; flexibility, untethered access, mobility and reduced implementation costs. And in wired IWOAN is reliable, robust and provides higher levels of bandwidth.

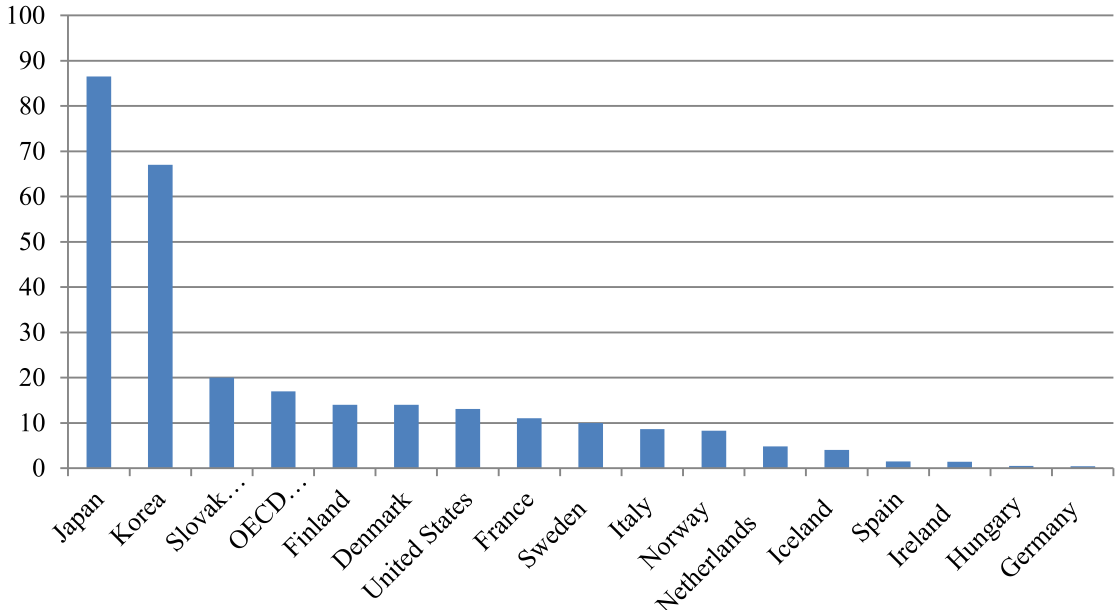

Figure 2.12: FTTH/B coverage (up to 2009)

In this section, we present the architecture of IWOAN, and the advantages of this integration. We will also investigate several issues that are raised with this type of integration that are found in related developments similar to IWOAN. Last we will discuss legacy placement algorithms and our goal for an energy efficient placement algorithm.

2.3.1 IWOAN Architecture

IWOAN is a cross-domain network of wireless optical architecture that combines the flexibility and efficiency of wireless with the security and stability of optical. The network consists of an optical back-end, typically a PON and a wireless access network in the front-end such as Wi-Fi, WiMAX and/or LTE. Shown in Figure 2.13, the PON network of IWOAN is employed from the OLT at the central office to the fibre optic end points at the ONUs. The wireless front-end is employed from the ONU to the BSs. A single OLT can run multiple ONUs and a single ONU can serve multiple BSs. IWOAN network topology functions like a tree; the OLT is the parent connected to the children ONUs and the BSs are the leaves of the ONU. A gateway is collocated with the ONU to function as an access point for BSs to connect wirelessly. The BSs communicate with the ONU in a multipoint-to-point method for uplink, and the ONUs communicate with BSs in a point-to-multipoint method for downlink. IWOAN communication can be done both in a wireless mesh network (WMN) method, or direct communication method. In the direct communication method for uplink communication, end-users generate packets of data to nearby BSs. These packets are then aggregated at the BSs and transmitted through their assigned wireless channels to the nearby ONU gateway. From the gateway, the ONU transmits the signals over fibre to the OLT, which are then routed to the rest of the internet. For downlink communication, the data packets are transmitted from the OLT to the ONUs. The packets are broadcasted to all ONUs, but only the destination ONU keeps the packet while other ONUs discard them. From ONUs to BSs, IWOAN is a unicast network; the packets are sent to the specified BS, and then to the specific end-user. The end-users of IWOAN can be both mobile and stationary.

The wireless mesh network method uses similar architecture with the difference being the BSs and ONUs can communicate to one another and traffic can take different routes to reach its destination. In this thesis we will not be using WMN method for communication, but instead will implement direct communication. When ONUs are located far from the central office, efficient spectrum modulation can be used from BSs to ONUs due to close proximity of the equipment (e.g. 64 QAM, QPSK, etc.), achieving higher levels of bandwidth [30].

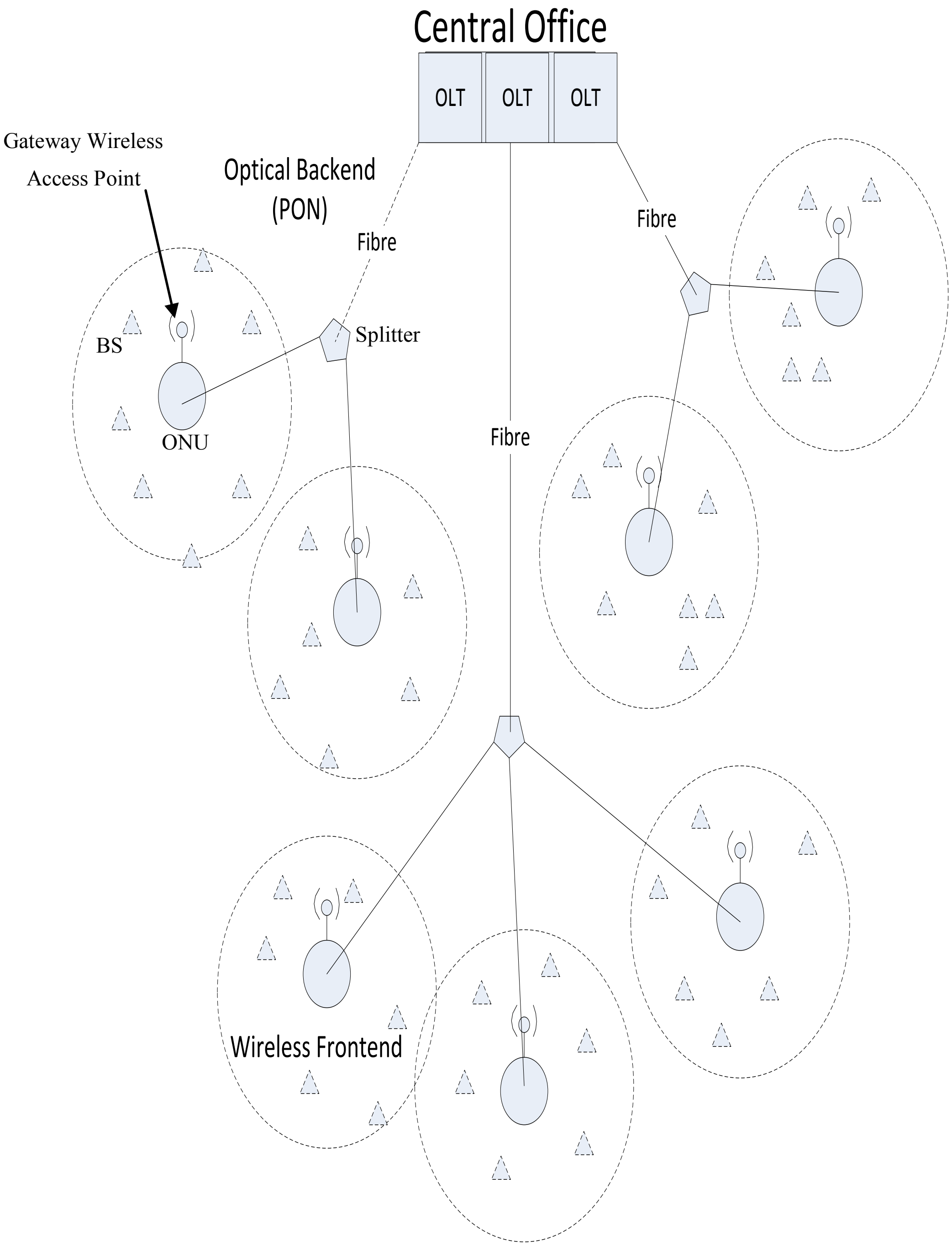

Figure 2.13: IWOAN architecture

2.3.2 IWOAN Advantages

Wireless-optical access is a very attractive architecture as running fibre to every home from the CO could be very costly. Also, due to spectrum limitations, it is not physically possible to provide wireless access from the CO to every end-user. The advantages of IWOAN are developed from existing research for a similar deployment of wireless optical access networks [30]. S. Sarkar *et al*. demonstrated that all BSs were able to transmit to one another by using a wireless mesh network at the front-end [31]. Several BSs in this network were set as gateways for the ONU to route the aggregate traffic to the OLT. The advantages of IWOAN range from costs, to accessibility, to survivability and reliability detailed below:

- In IWOAN a user will connect to a nearby BS through wireless or wired connection, and then to a nearby ONU in a wireless fashion. Expensive fibre deployment to each user is not required, producing a cost effective solution.
- The wireless aspect of IWOAN allows users within the BS coverage area, and the BSs within the ONU coverage area, to seamlessly connect to the network in an "anytime-anywhere" approach. This results in the capability of mobile connectivity.
- If a wireless mesh network (WMN) is implemented, IWOAN will be very robust in comparison to traditional wireless networks because it is a self organizing network. In the case of an ONU failure, the traffic will reroute through other nodes to an alternate ONU [30]. Seen in Figure 2.14, during the center ONU failure, traffic is rerouted through alternate routes. Our IWOAN utilizes a P2P connection rather than WMN, due to the factor that the power optimization is measured through traffic rates. If traffic takes multiple paths through several ONUs to reach the OLT, there will be more power consumption at each ONU consumed due to the increase in aggregated traffic.

- With recent trends of wireless and IMT-advanced specifications, IWOANs optical backhaul is capable of supporting higher levels of capacity delivered from the wireless front-end.
- IWOAN is more reliable than traditional wireless access networks. As in the case of low signal quality or failure of a part of the wireless network, users are able to communicate with alternate access points within transmission distance for both P2P and WMN [30].
- IWOAN is a quick and easy deployment. Deploying fibre in certain terrain conditions is physically impossible in some countries and very costly. IWOAN allows fibre to reach as close as possible to the user premises using PON. Thereafter, using "last-mile" wireless technologies, users can connect to the optical backbone.

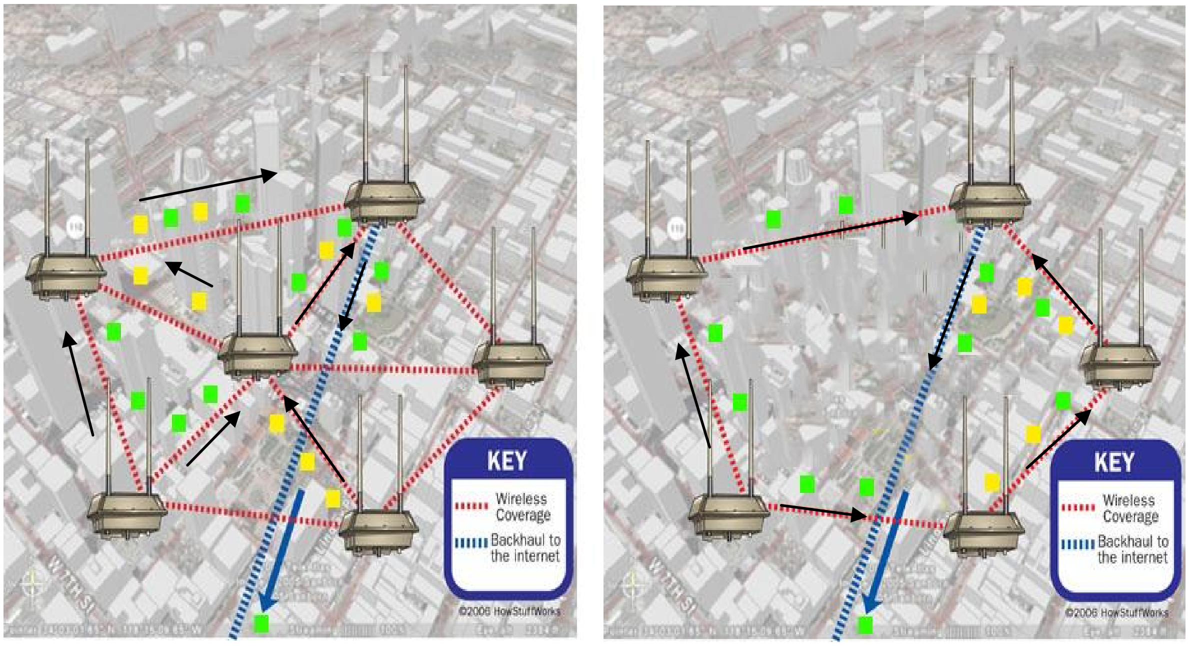

Figure 2.14: Self organizing wireless mesh network

2.3.3 Research Issues

The integration of wireless and optical results in significant advantages, but there are also several research issues that need to be resolved in order to make IWOAN more economical and implementable. S. Sarkar *et al.* state the research problems in [30],

- The placement of the network components such as the ONUs and BSs largely impact network performance. The point at which wireless and optical points meet is very critical to both deployment costs and efficiency of IWOAN.
- The routing of traffic in both uplink and downlink is important in the wireless front-end and optical back-end of IWOAN.
- In situations of network failure (e.g. fibre cut, high interference levels, gateway/BS failure, OLT/ONU failures), IWOAN requires self organizing properties and algorithms developed for survivability.
- Link scheduling is vital to all areas of access networks. It is equally important in IWOAN to increase throughput by reducing packet collisions.
- To achieve high levels of bandwidth in the wireless front-end of IWOAN, investigation into channel assignments must be made to help reduce signal interference. Orthogonal channel assignment techniques must be developed.
- The joint design of the two access methods must complement each other. IWOAN must be designed such that PON resolves the capacity limitation issues of wireless, while the wireless part resolves the costly "last-mile" reach of fibre penetrating to end-users. This will better enhance the performance of IWOAN.

In this thesis, our goal is to resolve the issue for placement of network components to enhance energy efficiency in IWOAN. To the best of our knowledge, there have not been any investigations in placement algorithms improving energy efficiency in IWOAN. There has been work done in placement algorithms optimizing distance, signal strength, signal propagation, and traffic [32, 33, 34, 35, 36], but none in optimization of energy efficiency for wireless optical access networks.

2.4 Placement Algorithms

A critical part of energy efficiency is dependent on placement of network components such as ONUs and BSs. The implementation of placement algorithms is left at the discretion of network operators, research and development. Based on literature review we discuss several placement algorithms for ONUs and BSs, transmitters, and wireless access points.

S. Sarkar *et al*. investigated how far fibre should penetrate before wireless access takes over [32]. Wi-Fi communication was used in the wireless portion, with ONUs serving as access points for BSs. The use of a multi-hop mesh network with stationary users allowed each user to reach one or more ONUs to direct their traffic to the OLT. The authors tackled the problem using a novel algorithm; placing multiple ONUs such that the average cost metrics (Euclidean distances) over all users with respect to a nearby ONU are minimized. A survey conducted in a neighbourhood of North Davis, California, provided data used to check the performance of the algorithm, which resulted in optimum placement locations for ONUs.

A more dynamic approach undertaken by Sarkar *et al*. uses the same architecture as in the work above [33]. Here, the access network is an "anycast" network, where end-users can connect to any one of the access points. The placements of ONUs play a key role for the cost optimization. To tackle this problem, they proposed the greedy algorithm for placing multiple ONUs in the network. Using the location of the wireless users, the authors found the optimal placement of multiple ONUs to minimize overall network costs (distance between users and closest ONU). Using greedy algorithm, the local optimum was achieved, and the problem was then reformulated as a global optimization problem by using simulated annealing (SA), and hill-climbing (HC) optimization algorithms. They have shown that SA and HC can improve chances of reaching a global optimum, with the greedy algorithm performing equally well in comparison to the global optimizers SA and HC.

Greedy algorithm is a method that makes a best decision at that moment in time. It builds up a solution piece by piece, choosing the next piece that offers the most obvious and immediate benefit [37]. The greedy strategy does not generally produce an optimal solution, but rather it will find a local optimum with hopes in finding the global optimum. Another algorithm used by Sarkar *et al* is simulated annealing [32]. This is a generic probabilistic scheme for locating the global optimum, used when the search space is discrete, and the goal is to find an optimal solution in a fixed amount of time. The other algorithm used is HC. This method is a mathematical optimization technique that starts with an arbitrary solution to a problem and attempts, in increments, to find a better solution.

In the work done by H. Sherali *et al*., optimal locations for transmitters for micro cellular radio communications are determined using minisum, minimax and convex combination of minisum and minimax objective functions [34]. A good transmitter location will result in an acceptable coverage performance by the transmitter using a minimum amount of power, resulting in lower co-channel interference and improved frequency re-use. The authors addressed the problem of locating a single transmitter or a set of multiple transmitters over a specified coverage region, such that the signal at various potential receiver locations is of sufficient intensity. This is a simple facility location problem, requiring transmitters in a service facility to serve all receivers in the design space.

S. Hurley demonstrated a method to select a set of sites from a list of candidate sites [35]. The selected sites form the basis of a network that must satisfy network requirements such as high area coverage and high traffic capacity, but also minimize infrastructure costs. The author used an optimization framework based on simulated annealing for BS selection and configuration. He used a cost model with a weighted additive cost function consisting of coverage, site cost, traffic, interference and handover costs.

R. Battiti *et al*. used HC, SA, and tabu and reactive search to find optimal placements for wireless access points [36]. Most wireless networks are based on the cellular theory, where several radio access points are placed throughout the region and act as relays between the radio network and fixed network. To determine wireless access point placements the authors proposed a method to integrate coverage requirements with reduced error and user position estimation. The user position estimation method is based on strength of the radio signals received from multiple wireless access points. HC was used as the local search strategy where the access point coordinates are searched for in the optimal configuration. The initial step is random or generated preprocessing, and then slight changes of the configuration are done until the local minimum is found. Due to the drawback of the inability of HC to escape the local minimum of the cost function, a simulated annealing technique was used. The third approach used in this paper was tabu and reactive search. This technique requires much more computation time, as it is a history sensitive generalization of the local search heuristic algorithm for discrete optimizations. Tabu and reactive search are able to find the global minimum of the cost function through a memory based feedback scheme.

In this section we presented various proposals of placement algorithms. Some of these algorithms were initially developed for wireless systems but show potential when implemented in wireless optical systems. Although the algorithms are not perfect in finding optimal values due to limitation in certain optimization algorithms, they work to obtain better results with the use of alternate optimization techniques. Nevertheless, the background information and concepts presented in these algorithms provide a solid foundation for future work. In our thesis we propose a placement algorithm in which we try exhaustive search method, where we search every possible location within a specified coverage area and optimize each location for an energy efficient deployment.

2.5 Energy Efficient Models and Methods

To develop an energy efficient wireless optical integration, we must look at energy consumption models in both wired and wireless access networks. According to Baliga *et al.*, the ultimate capacity of the Internet might eventually be constrained by energy density limitations and associated heat dissipation considerations rather than by the bandwidth of the physical components [39].

An energy management mechanism is proposed by Yan & Dittmann for a downlink EPON system [40]. The idea is to put the ONU into sleep mode and determine a suitable wake up time scheduler at the OLT. This approach has been widely used in wireless networks for saving battery power in mobile stations. The OLT sends a control message with the sleep period to the ONU. The message contains the sleep parameters for the ONU's start and wake-up times. After the scheduled wake up time, the ONU transits back into wake mode and waits for another control message from the OLT. In this approach, the control of energy efficiency is through the OLT.

Investigations of the present cost and energy perspective on network design for IP-based WDM networks were conducted by Parthiban *et al.* [41]. This papers objective determined the energy consumption of the network. The authors used a model of the network that includes information about quantity and power consumption of various types of Cisco model equipment in the network (Figure 2.15) [42]. This model was used to calculate the network power consumption as a function of the access rate to customers, with power consumption measured in the metrics of energy per bit. The authors discussed energy in access networks, more specifically in PON. For access rates up to 100 Mbps, PON infrastructure consumed the least energy in comparison to fibre to the node, point-to-point Ethernet over optical and WiMAX. Figure 2.16, shows the average energy per bit for routers as a function of throughput [41]. We developed our power coefficient based on the values from Figure 2.16; for throughput of 1 Mbps to 1 Gbps the energy per bit ranged from greater than 1000 *nJ/bit* to 100 *nJ/bit*.

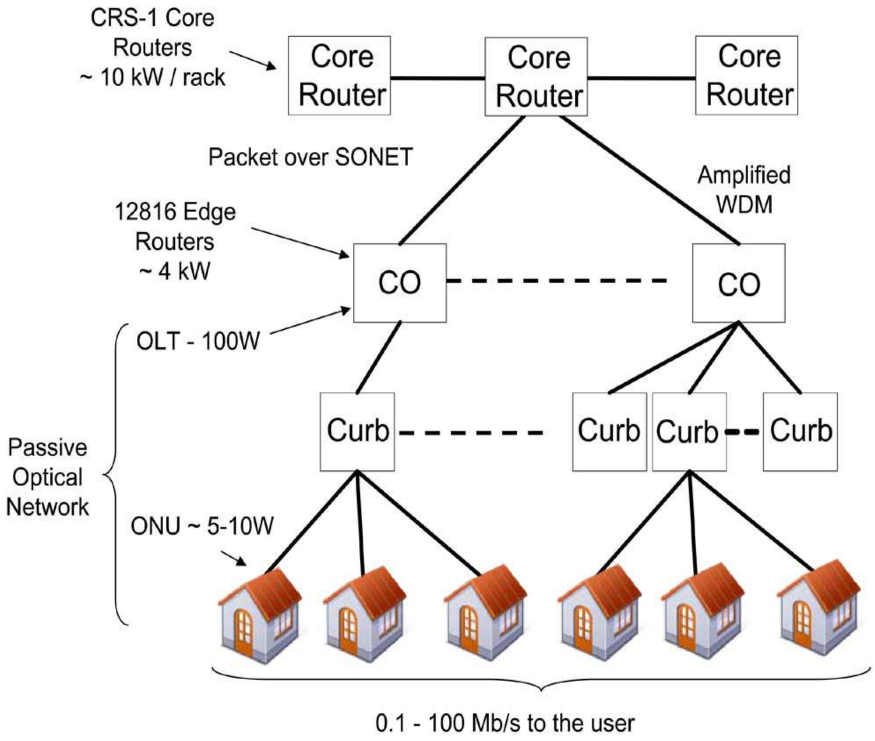

Figure 2.15: Power consumption of the public Internet

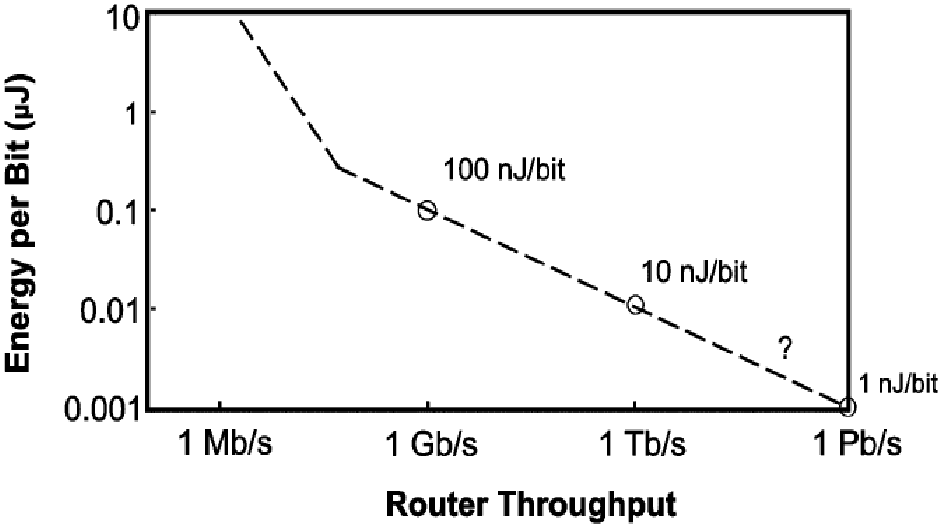

Figure 2.16: Energy consumed per bit in routers

Zhang & Gorce proposed an energy efficiency metric, energy distance ratio per bit (EDRb), for wireless sensor networks [8]. EDRb is the measurement of the amount of energy exhausted during the transmission distance of traffic. By minimizing EDRb, optimal hop distance is achieved for which related optimizations such as optimal transmission power, optimal signal noise ratio, and optimal bit error ratio is obtained. The energy metric used in this paper is also modeled in our thesis as energy per bit per meter (nJ/bit/m). The problem is formulated as optimizing the energy consumption per correctly received bit. The energy model used is based on transmitting a packet that is made of two parts: energy consumed at the transmitter and at the receiver. The transmitter and receiver are composed of the start up power and the number of bits per frame over the bit rate. In the transmitter they use amplifying power, whereas in the receiver they account for internal component (hardware) power.

A more dynamic approach for power consumption model is through a static power component and dynamic component. Richter *et al.,* devised a power consumption model that took into consideration realistic input parameters. This model is used to measure the total network power consumption in mobile communication networks [43, 44]. The power consumption of a BS will consist of two parts: a static power figure consumed in an unloaded BS, and a dynamic power figure dependent on the load situation. In our thesis we model the power consumption similar to this model as the gateway co-located with the ONU is very similar to a BS, but with a much larger transmission distance. We model the power consumption to consist of a static power of an ONU start up, and a dynamic power dependent on traffic and transmission distance, as the load.

Chapter 3

System Model Development and Overview

3.1 IWOAN Hierarchy

In this thesis we employ a hierarchical wireless-optical network access model. A three layer architecture is proposed for uplink and using multipoint-to-point topology. The wireless BS at the front-end forwards the aggregate traffic (sent from the users) to the wireless gateway co-located with the ONU. The gateway serves as a local access point for all BSs that are communicating to the assigned ONU. These gateways are the midpoint for both the wireless and optical world. Communication between BS and ONU is through standard wireless technologies (e.g. WiMAX, LTE and Wi-Fi). Individual channels will be assigned to BSs to transmit to ONUs. Traffic from the ONUs is then aggregated and forwarded to the OLT via fibre optical cables. The back-end of this hierarchy is PON architecture (Figure 2.13).

3.2 Channel Assignment Method

We assign the wireless communication channels between BS and ONU using two methods: random channel assignment method and channel reuse method (CRM). The random channel assignment method is done through the cumulative distribution function (CDF) and the probability of choosing one channel out of a group of channels. With the random probability channel assignment method, available channels are assigned to BSs with equal probability.

The CRM, also known as frequency reuse pattern, is a key function used in cellular networks in reusing frequency channels. We use this method of channel assignments to compare and justify that random channel assignment method is as efficient as CRM. The CRM reuses seven channels throughout our network based on cell structures. The elements that determine when a channel can be reused (assigned) are the reuse distance and the reuse factor [45]. We use these *D* and *k* when assigning channels using channel reuse method, this can be seen in detail in channel assignments for Figure 5.2 our cell heuristic in SFNet. These rules must be followed in order for CRM to work as designed. The reuse distance of an assigned channel, *D* is calculated as:

$$D = R\sqrt{3N}, \tag{3.1}$$

where *R* is the radius of the cell and *N* is the number of cells per cluster (Figure 3.1). The channel reuse factor is the rate at which the same channel can be used in the network. It is modeled as:

$$\frac{1}{K}, \tag{3.2}$$

where *K* is the number of cells which cannot use the same channel for transmission. A cell is designed as a hexagonal shape. If a channel is assigned to a cell it cannot be assigned to any of the six cells adjacent to it.

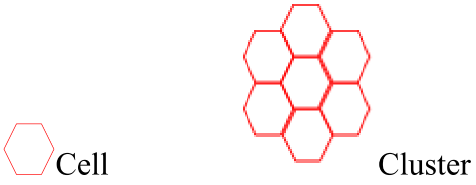

Figure 3.1: Cell and cluster

3.3 Carrier to Interference

Carrier to interference (C/I) ratio has been used in practice to show the signal power over the average received co-channel interference. C/I ratio, expressed in dB, is the ratio between a desired carrier (C) and an interfering carrier (I). C/I ratio is used to determine whether an interference level is acceptable or not. The ratio's objective is to protect wireless systems against interference from other wireless systems by providing a minimum separation from those systems. Factors that affect interference vary, with the main factors being route design and equipment design. Fundamentally, interference is caused by the closeness of other BSs sharing the same frequency channel. Wireless communication antennae use a highly focused beam that is determined by equipment design [46]. Other equipment design factors that affect interference are frequency selection, modulation schemes and signal polarization.

To maintain reliable service, the ratio of the received signal to the interfering signal should always be larger than the threshold value. Co-channel interference is defined as the interference experienced between two adjacent BSs transmitting to two neighbouring ONUs using the same channel [4]. Co-channel interference may exist between adjacent BSs i and i' where BS_i uses wireless channel j to transmit data to ONU_k, and $BS_{i'}$ uses the same channel to transmit to an $ONU_{k'}$ (Figure 3.2). The BS transmission distance is shown as a circle in Figure 3.2, this is the case for both random channel assignment method and channel reuse method. We use the following model to measure co-channel interference [4]:

$$I_{ii'} = \left[\frac{R_{i'}}{D_{ii'}}\right]^{\gamma}, \tag{3.3}$$

where $I_{ii'}$ is the co-channel interference caused by $BS_{i'}$ on BS_i, $R_{i'}$ is the $BS_{i'}$ transmission distance, $D_{ii'}$ is the distance between BS_i and $BS_{i'}$, and γ is an environmental factor dependent on buildings, and structures surrounding the proposed development [4]. Since co-channel interference weakens the signal quality, an increase in the number of ONUs is required to support the BS for error free transmission. The increase of ONUs is a result of meeting acceptable interference levels. To do this we must increase the signal quality by using alternate channels, either by activating more ONUs or utilizing channels that are available. In order to deal with co-channel interference, channel assignment and signal quality must be managed in our algorithm.

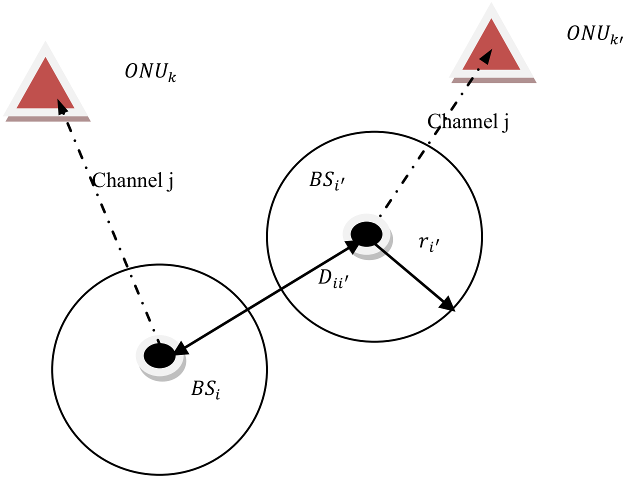

Figure 3.2: Co-channel interference between BSs

3.4 Power Coefficient Model

We model the power consumption at an ONU as the sum of a constant (static) part per start-up (bootstrap power) and dynamic part during equipment operation. The ONU specifications such as channel assignments, transmission distances, traffic capacity, bootstrap power and dynamic power are set by the service provider and network designer. We determine the fixed bootstrap power component based on data obtained from NEC Global and Hitachi datasheets, with the ONUs requiring bootstrap power of 5 Watts (W) [47, 48]. The dynamic power component, dependent on load situations, is a linear function measured by the product of the transmission distances and traffic rates for our first formulation (P_d):

$$P_d = \beta \lambda_i D_{ik}, \tag{3.4}$$

where β is a power coefficient in energy per bit per meter [8], λ_i is the traffic rate of BS_i, and D_{ik} is the transmission distance from BS_i to ONU_k. In the second formulation we utilize the same static power component, however the dynamic power component is modified. The second dynamic power consumption ($P_{d'}$) is also a linear function of traffic rates:

$$P_{d'} = \alpha \lambda_i, \tag{3.5}$$

where α is the power coefficient in energy per bit [7], and λ_i is the uplink traffic rate of BS_i. These two equations are proposed by us as linear equations. This is due to the fact that the entire set of variables are continuous (i.e. can take fractional values). There is a single objective of minimizing power consumption. And finally, the objective and constraints are linear (i.e. all terms are either a constant or a constant multiplied by an unknown variable). These equations are obtained from research completed in works [7, 8] where the power coefficients are used to model energy consumption in wireless and optical access networks.

3.5 System Model Algorithm

Next, we show how we compute the placement of our ONUs for our network and minimize our objective formulation, refer to Figure 3.3 for flowchart diagram:

1. Deploy all possible ONU locations.
2. Initialize several random possible ONU locations to be active.
3. Assign a random channel to BS to transmit to an active ONU.
4. A given BS attempts to connect to the nearest active ONU that is within ONU transmission distance.
5. If assigned channel for BS is not in use by the ONU and the upper bound on number of connections and capacity of ONU has not been breached, allow connection.
6. Check if C/I threshold constraint has been voided. If voided, restart channel assignment for all BSs (certain channel has been used numerous times when randomly selecting channels, therefore reset all), start from BS 1; go to step 2.
7. Repeat steps 3 - 6 for all BSs; if step 4 fails go to step 8; if step 5 fails go to step 9; otherwise after all BS are connected; go to step 10.
8. If there are no active ONUs within ONU transmission distance of a given BS, initialize a new possible ONU location to be active within ONU transmission distance of BS; go back to step 4.
9. Attempt to connect to the next active ONU that is within ONU transmission distance; if step 9 fails go to step 8.
10. Turn off active ONUs that are not in use by BSs.
11. Calculate and store power consumption; go back to step 2 until all possible ONU location combinations have been tried, store data results until the minimum number of active ONUs and power consumption are achieved (exhaustive search is used here). Output minimum power consumption.

Due to randomization of channel assignments we rerun the simulation numerous times until we achieve a common minimum power consumption.

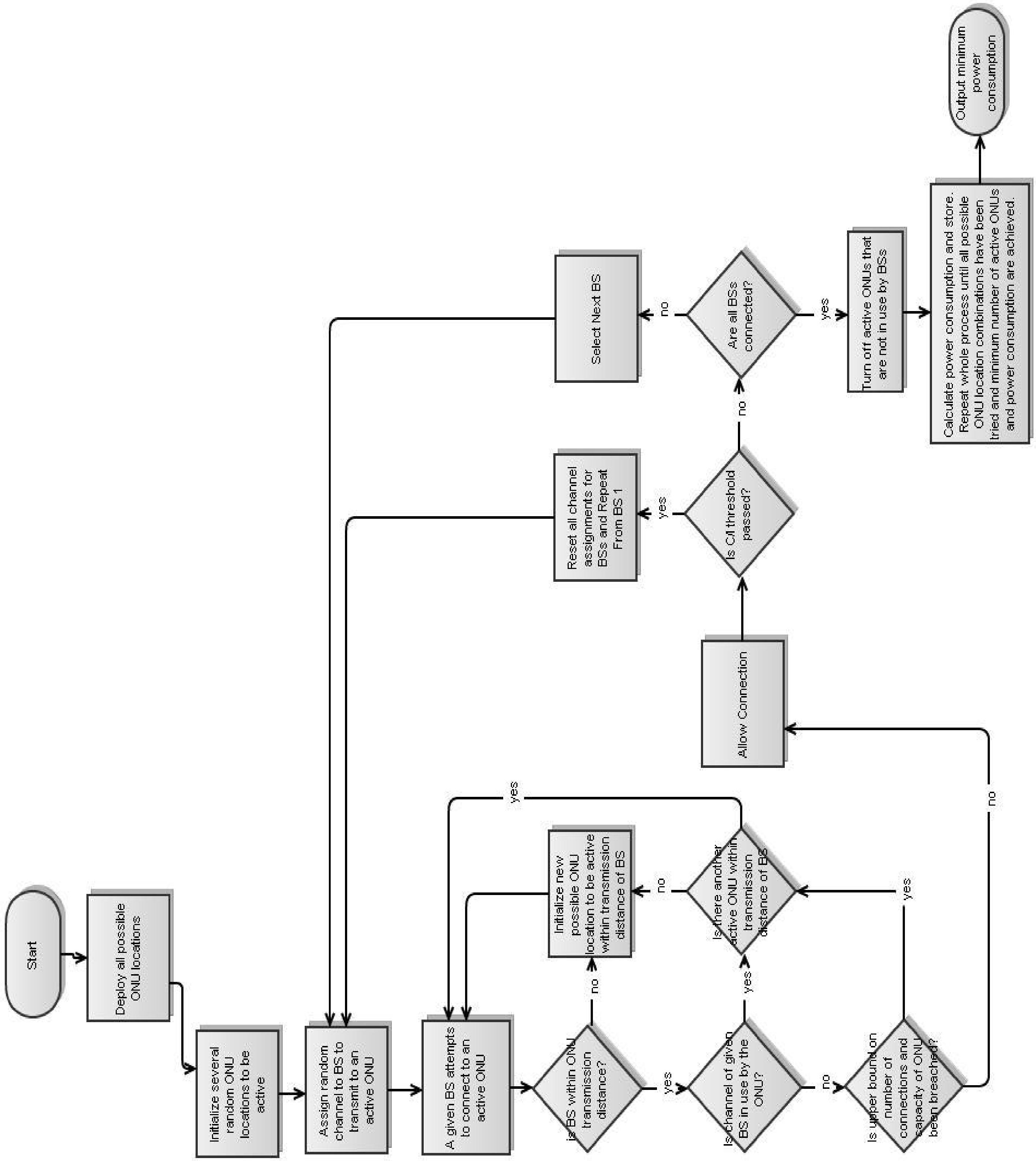

Figure 3.3: System model algorithm flowchart

3.6 Downlink Implementation

Our work in this thesis is developed for uplink communication. We do not model downlink communication in this thesis, as our constraints and parameters are developed for uplink. For future work we provide some guidance in this section to develop an algorithm that will handle downlink communication. One must follow the steps listed below:

1) Devise an alternative formulation that incorporates the traffic that is being delivered to the BSs, rather than from the BSs.
2) Develop an alternative co-channel interference constraint that models the interference exposure for downlink communication. The co-channel interference equation must also be adjusted to incorporate the parameters of the ONU.
3) The downlink traffic must be managed such that the upper bound capacity of the ONU is not surpassed.

Some guidance towards downlink communication is provided above, more work is needed for the network to function as it does for uplink. The foundation can be built upon the current work done here.

Chapter 4

Mathematical Formulation for Optimal Placement of ONUs and Minimum Power Consumption

Our goal in this study is to find optimal ONU placements while minimizing power consumption for IWOAN. We obtain optimal locations using a linear formulation that factors transmission distance and aggregation of traffic to the ONU as a direct influence on power consumption. As we minimize power consumption, we also minimize the number of active ONUs required to service the traffic. Idle ONUs will be shut down when they are not in use, or connected to any BSs. We evaluate this network model in an environment developed on CPLEX optimization studio. The formulation is simulated using mixed integer linear programming, as some variables (such as $I_{ii'}$) can take non-integral values. We use integer values for decision variables and linear and quadratic conditions to maintain our constraints. Section 4.1 lists parameters which were selected to remain constant during subsequent model testing. Decision variables for optimization purposes are also listed in section 4.1. The mathematical formulation is detailed thereafter in Section 4.2 with (4.1) as the first formulation, and (4.2) as the second modified formulation. The constraints can be found in section 4.3.

4.1 Parameters and Decision Variables

For the sake of generality, the capability of handling a heterogeneous model is developed by choosing the values of parameters. In our model, BSs are associated with the following attributes: Uplink traffic rate, locations, and transmission radiuses. ONUs are associated with: possible locations, transmission radiuses and wireless channels for ONUs, bootstrap power, and power coefficient. Locations below refer to (x, y) coordinates. These parameters are listed below in Table 4.1, refer to Figure 1.3 for a clearer understanding of the parameters such as R_i, T_k, D_{ik}, and $D_{ii'}$ can be seen in Figure 3.2.

Table 4.1: Fixed integer parameters

B	set of fixed locations for BSs	λ_i	uplink traffic rate of BS_i
O	set of possible locations for ONUs	I	maximum acceptable interference
W	set of available wireless channels per ONU	G	an arbitrarily large number
C	number of channels needed to support uplink traffic from BS	P	bootstrap power
A	upper bound on number of channels per ONU (i.e. $C \leq A$)	β	power coefficient (in nJ/bit/m)
R_i	transmission distance of BS_i	α	power coefficient (in nJ/bit)
T_k	transmission distance of ONU_k	D_{ik}	distance from BS_i to ONU_k
J'	upper bound for the capacity of ONUs (i.e. upper bound for parameter J_k to be introduced later in the thesis)	$D_{ii'}$	distance from BS_i to $BS_{i'}$

Decision variables are then listed in Table 4.2.

Table 4.2: Decision variables

U_k	Binary variable denoting if ONU_k is installed. $U_k \in \{0, 1\}$, 0 denotes ONU not installed, and 1 denotes ONU is installed.
G_{ik}	Binary variable denoting if ONU_k is connected to BS_i. $G_{ik} \in \{0 ,1\}$, 0 denotes BS_i is not connected to ONU_k, and 1 denotes ONU_k is connected to BS_i.
X_{ji}	Binary variable denoting if channel j is assigned to BS_i. $X_{ji} \in \{0, 1\}$, 0 denotes channel j is not assigned to BS_i, and 1 denotes channel j is assigned to BS_i.
Y_k	Binary variable denoting if ONU_k is active. $Y_k \in \{0, 1\}$, 0 denotes ONU not active, and 1 denotes ONU is active.
J_k	capacity of ONU_k
$I_{ii'}$	Co-channel interference of $BS_{i'}$ on BS_i $(I_{ii'} = [\frac{r_{i'}}{D_{ii'}}]^{\gamma})$

4.2 Mathematical Formulation

Mathematical formulations detailed below obtain our minimum power consumption.

$$P_t = min\{\sum_{k\in O} PY_k + \sum_{k\in O} \sum_{i\in B} \beta\ G_{ik}\lambda_i D_{ik}\} \tag{4.1}$$

$$P_t = min\{\sum_{k\in O} PY_k + \sum_{k\in O} \sum_{i\in B} \alpha\ G_{ik}\lambda_i\} \tag{4.2}$$

In (4.1), the ONUs power consumption consists of three components: a fixed start up component that is based on Y_k, if an ONU is activated or not ($\sum_{k\in O} PY_k$), and; two dynamic components: traffic rates λ_i and transmission distances D_{ik} based on G_{ik}, if ONU_k is connected to BS_i. P is the bootstrap power, a fixed value dependent on start up power requirements of ONUs. In (4.2), the fixed start up component is the same as (4.1). The dynamic component is modified to consist of traffic rates λ_i based on G_{ik}, if ONU_k is connected to BS_i. The baseline assumption is that the gateway co-located with the ONU has a fixed bootstrap power of P. The power coefficient β and α is assumed to be a fixed value and uniformly linear for all traffic and transmission distances. The objective of the above two formulations is to minimize the sum of the static power and the dynamic power. We develop (4.2) to separate the power consumption component due to the transmission distance from the power consumption component due to the traffic rate. Due to assumptions made in our work, these results from our formulations are a rough estimate of the power consumed in transmission; it is an ideal scientific result dependent on our inputs. Accurate results can be obtained with the use of more accurate values in energy consumption of traffic in wireless optical networks.

4.3 Constraints

Channel Assignment Constraints: Equation (4.3) states that the decision variable X_{ji} must be binary. In constraint (4.4), the number of channels assigned to BS shall not exceed more than the number of channels required to support the BS traffic. In constraint (4.5), once a channel is assigned to a BS it could not be used again in the same group of BSs that are connected to the same ONU_k. We make a fundamental assumption that BSs each take one channel. In constraint (4.6), the total BS connections shall not exceed the total number of channels supported by the ONU. We assume that a given BS can only communicate with a given ONU through one channel.

$$X_{ji} = 0 \; or \; 1 \; \forall j \in W, i \in B; \tag{4.3}$$

$$\textstyle\sum_{j \in W} X_{ji} \leq C \; \forall i \in B; \tag{4.4}$$

$$\textstyle\sum_{i \in B} G_{ik} X_{ji} = 1 \; \forall k \in O, j \in W; \tag{4.5}$$

$$\textstyle\sum_{i \in B} G_{ik} \leq Y_k A \; \forall k \in O; \tag{4.6}$$

ONU Installation Constraints: Decision variables G_{ik} , U_k, Y_k must be binary (Equations (4.7 - 4.9)). In equation (4.10), the BS can only connect to an ONU if that ONU is turned on. However, in Equation (4.11), an ONU can only be turned on if it is installed at the specified location. Equation (4.12) states that each BS can only be connected to one ONU. In Equation (4.13), for a BS to connect to an ONU it is established that the distance from the BS and the ONU must be less than the transmission distance of the ONU.

$$G_{ik} = 0 \; or \; 1 \; \forall i \in B, k \in O; \tag{4.7}$$

$$U_k = 0 \; or \; 1 \; \forall k \in O; \tag{4.8}$$

$$Y_k = 0 \text{ } or \text{ } 1 \; \forall k \in O; \tag{4.9}$$

$$G_{ik} \leq Y_k \; \forall i \in B, k \in O; \tag{4.10}$$

$$Y_k \leq U_k \; \forall k \in O; \tag{4.11}$$

$$\sum_{k \in O} G_{ik} = 1 \; \forall i \in B; \tag{4.12}$$

$$G_{ik} D_{ik} \leq T_k \; \forall i \in B, k \in O; \tag{4.13}$$

Network Capacity Constraints: Equation (4.14) enforces that the sum of aggregated traffic from the BSs connected to ONU_k is less than the upper bound of the traffic supported by ONU_k. Equation (4.15) is the nonnegativity constraint of decision variable J_k, (capacity of ONU_k) .

$$\sum_{i \in B} \lambda_i G_{ik} \leq J_k \; \forall k \in O; \tag{4.14}$$

$$0 \leq J_k \leq J' Y_k \; \forall k \in O; \tag{4.15}$$

Signal Quality Constraints: The goal of the fourth set of equations is to establish signal quality limits. Equation (4.16) is the nonnegativity constraint of decision variable $I_{ii'}$ (co-channel interference of $BS_{i'}$ on BS_i). In Equation (4.17), tolerable system interference is set below the maximum acceptable interference using co-channel interference model [4]. Since co-channel interference will impact the signal quality of the wireless channels, we need to take this into consideration when we decide on channel assignment for individual BSs. In Equation (4.17), the left hand side is the total co-channel interference introduced to BS_i by other BSs using the same channel j. When $X_{ji} = 0$, the right hand side will be equal to G (a very large number), thus the constraint will always be satisfied. However, when $X_{ji} = 1$, the right hand side will be equal to $\frac{1}{I}$, guaranteeing the signal quality to be at least the threshold of an acceptable

C/I. We use $\frac{1}{I}$ as the C/I because it is the quotient between the average modulated carrier power and the average co-channel interference power *I*. All co-channel interferences must be below this upper bound ratio.

$$0 \leq I_{ii'} \ \forall (i, i') \in B, i \neq i'; \tag{4.16}$$

$$\sum_{i' \epsilon B,\, i' \neq i} I_{ii'} X_{ji'} \ \leq G + \left(\frac{1}{I} - G\right) X_{ji} \quad \forall j \in W, i \in B \tag{4.17}$$

Chapter 5

Simulation Results and Setup

We have developed an in-house simulation of the IWOAN architecture described in Section 3 and Section 4 using C++ on CPLEX. The simulation covers 1600 m^2 area of downtown San Francisco, referred to as SFNet [30]. This area has an estimated population of 15,000 residents, whereas greater San Francisco has an area of nearly 75.2 km^2 with a population of 745,000. Therefore, the population of SFNet's area is quite representative of San Francisco's population density of approximately 9600 people/km^2. Shown in Figure 5.1[1], SFNet expands from approximately Golden Gate Ave. and Divisadero St. intersection to Golden Gate Ave. and Van Ness Ave. intersection and from Divisadero St. and Pacific Ave. intersection to Van Ness Ave. and Pacific Ave. intersection. SFNet consists of 25 wireless BSs in fixed locations (coffee shops), where they will function as access points to mobile and stationary users. Figure 5.1, is built as a grid using (*x, y*) coordinates, with each increment in an x or y direction accounting for 100 m in distance. We also simulate a heuristic of SFNet's grid design. This heuristic model of SFNet (Figure 5.2)[1] is used for our channel reuse method (CRM) approach. Dependent on channel reuse distance and factor the numbers in each cell represent a channel (i.e. 0 → channel 0, 1 → channel 1, 2 → channel 2 etc...)

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[1] map courtesy: Google Maps

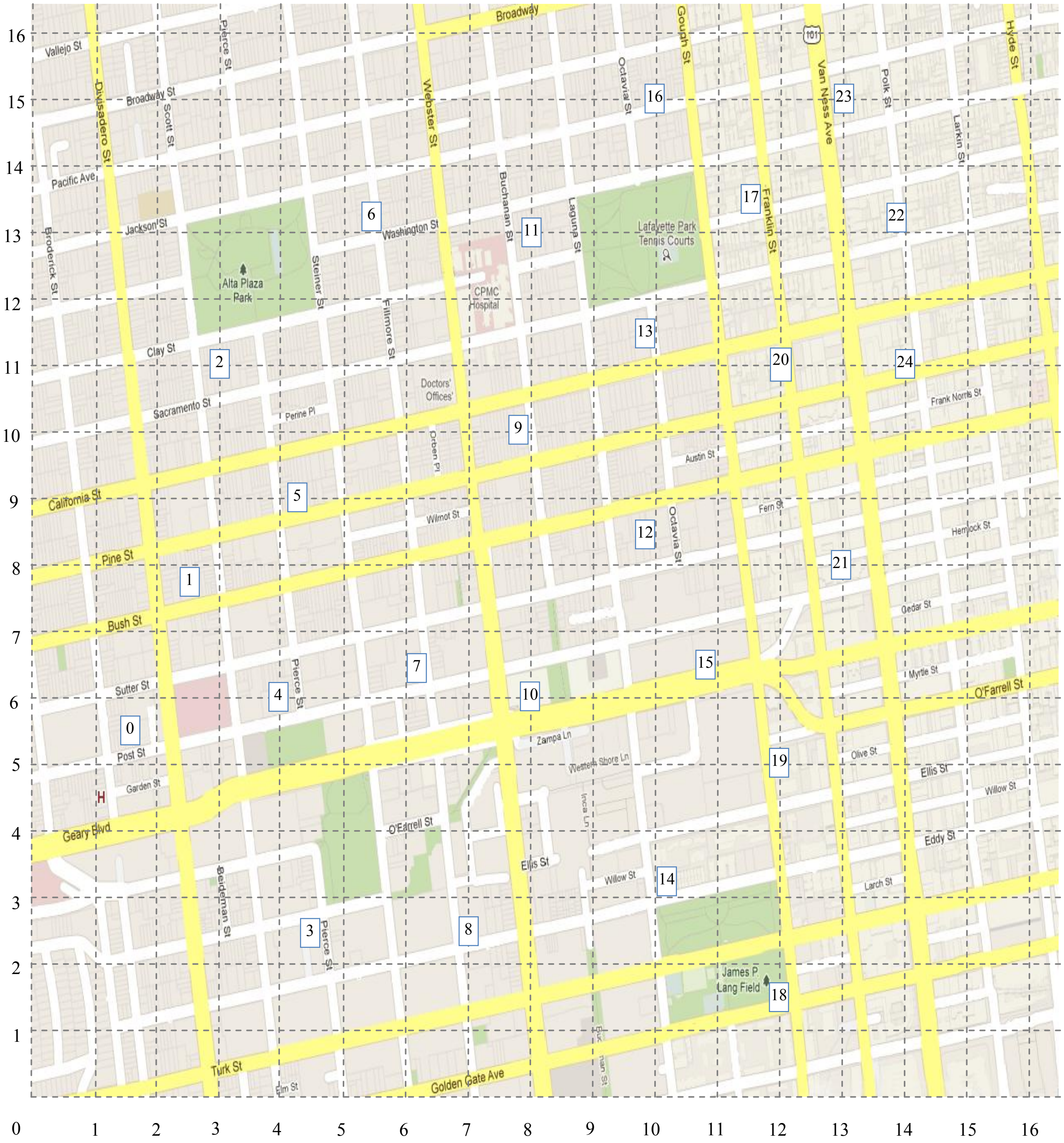

Figure 5.1: San Francisco SFNet

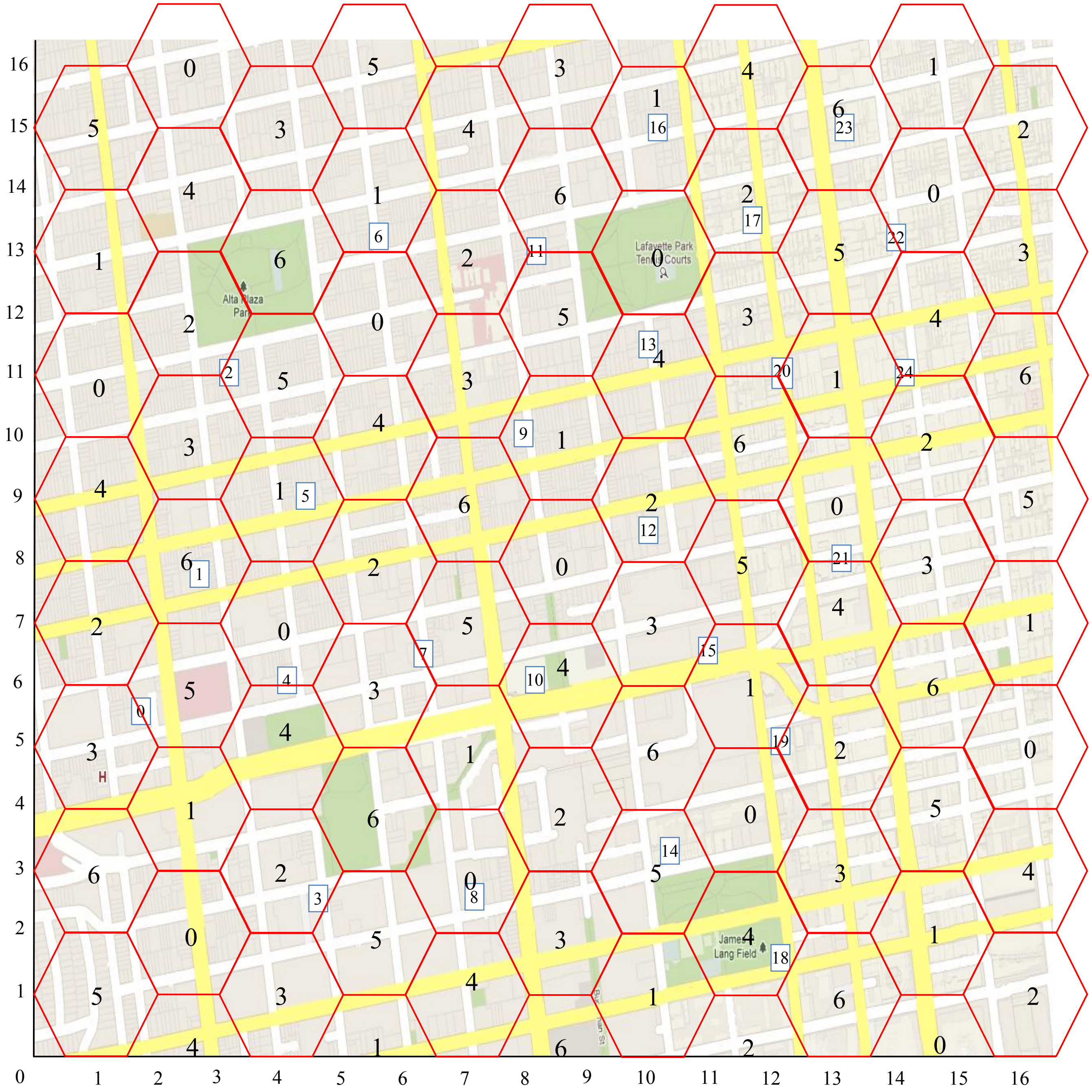

Figure 5.2: San Francisco SFNet with cell heuristic

We have used a homogenous network model in the simulations presented in this thesis, in which the parameters of all base stations are set equal to each other. The same condition is applied to all ONUs, where their parameters are set equally as well. The simulations were conducted to: 1) investigate how the initial placement of ONUs will affect our power consumption; 2) adjust the transmission distance of ONUs to see their effect on the power consumption; 3) investigate how the network will behave with a heavier load by increasing the number of BSs; and 4), develop a heuristic for the placement of ONUs by imposing a cell structure grid and channel reuse method for channel assignments to compare to our square grid and random channel assignment method. We determine the fixed bootstrap power component based on the data obtained from NEC Global and Hitachi datasheets, with the ONUs requiring a bootstrap power of 5 W [47, 48]. The BSs are at fixed locations with the transmission distance of each BS $R_i = 100$ m, transmitting traffic at a rate of $\lambda_i = 100Mbps$ per BS. With recent wireless innovations 100 Mbps uplink is reasonable, this is justifiable due to the standards of (IMT)-Advanced having peak data rates of up to 1 Gbps in the downlink, and up to 500 Mbps in the uplink [5]. ONUs have a transmission radius of $T_k = 400$ m, with the capacity to support $J' = 1Gbps$, and $W = 10$ wireless channels. Wireless transmission can be sent at large distances; in WiMAX at 20 MHz, BSs can transmit at 75 Mbps with a transmission radius of 800 m [4]. Therefore we assign an ONU transmission radius of 400 m to be reasonable, as the ONU gateway functions as a BS capable of reaching larger or smaller transmission radiuses. We set the maximum acceptable interference to $I = 5dB$. We must first determine an optimum value for the power coefficient. We calculate the optimum power consumption as a function of power coefficient β, when β varies from $1nJ/bit/m$ to $10nJ/bit/m$ [7, 8]. We use this simulation to obtain a reasonable value for β. The possible locations for ONUs are placed in every (*x, y*) coordinate (i.e. ONU0 will be located at coordinate (0, 0), ONU1 at coordinate (1, 0)). In Figure 5.3, we observe that the Minimum power consumption linearly increases as a function of the power coefficient.

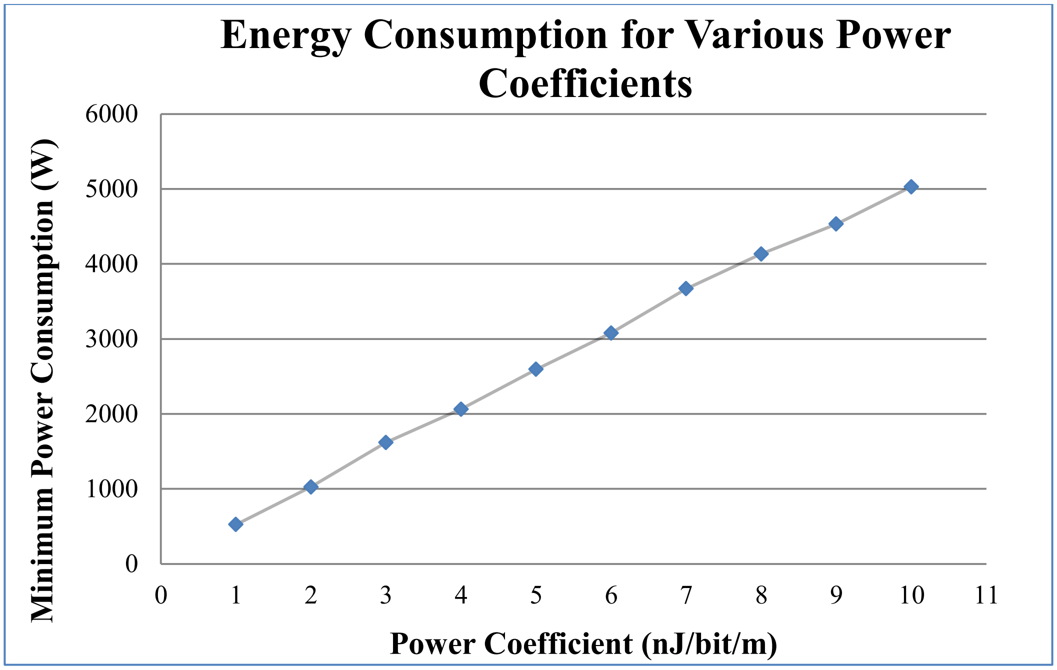

Figure 5.3: Energy consumed for each bit of data transmitted per meter

In the next simulations, we will use the median value of β, that is $\beta = 5.5nJ/bit/m$, to study the effect of other network parameters on the power consumption. We use this median value to simulate the effect on power consumption as no specific value has been determined in previous research.

5.1 Effect of Initial ONU Placement on Power Consumption

To investigate the effect of initial placement of ONUs on power consumption we place ONUs at different initial possible locations in SFNet. Our algorithm will search for the optimal locations to install and activate ONUs. We simulate five scenarios in which we place ONUs at (*x, y*) coordinates. In Scenario 1, we place the ONUs 100 m apart from one another, at every (*x, y*) coordinate where x and y are 0, 1, 2… In Scenario 2, we place ONUs a distance of 200 m apart from one another, at every (*x, y*) coordinate where x and y are 0, 2, 4, 6… and so forth. Increasing the distance between the ONUs in increments of 100 m up to 500 m in scenario 5. Our inputs to the system are as follows: $P = 5W, R_i = 100m, \lambda_i = 100Mbps,\ T_k = 400\text{m}, J' = 1Gbps, W = 10$ and $I = 5dB$. These inputs are consistent for all five scenarios. In Figure 5.4, we present the minimum power consumption alongside the traffic power component and the transmission distance power component. The results are obtained from Equations (4.1), and (4.2). Recall Equation (3.4) $P_d = \beta\lambda_i D_{ik}$ the dynamic traffic and transmission distance power component and Equation (3.5) $P_{d'} = \alpha\lambda_i$ the dynamic traffic power component. For all BSs and ONUs that are connected and activated. The traffic power is defined by, the product of the uplink traffic rate from BSs and the power coefficient will result in the traffic power component. For all BSs and ONUs that are connected and activated. The traffic and transmission distance power component is defined by, the product of the power coefficient, uplink traffic rate from BSs and the distance between the connected BS and its ONU. To obtain a rough estimate for transmission distance power, we subtract the traffic and transmission distance power from the traffic power.

$$P_{transmission} = P_d - P_{d'}$$

Each ONU consumes 5 W of power to be active. Table 5.1 details the values that are presented in Figure 5.4, explaining the minimum power consumed in the five scenarios ranges from 2776 W to 3379 W. The figure represents power consumption of ONUs at different initial locations ranging from 100 to 500 m. We notice that the traffic power shown in black is stagnant throughout each scenario due to the traffic that is consistent at 100 Mbps per BS. The transmission distance power shown in grey increases through the five scenarios. This result is from fewer initial possible locations available in Scenario 5 compared to Scenario 1. When there are more possible locations available, and there are fewer active ONUs, the power consumption is at its minimum. Also, the possibilities of having a shorter distance between initial ONU placements and BSs increases when there are more possible ONU locations available. Thus, the power consumption in each scenario is dependent on the number of initial possible locations for ONUs, and the locations selected to be active.

There are a total number of 289 possible locations for the ONUs in Scenario 1 whereas, in Scenario 5 there are a total number of 16 possible locations (Table 5.1). In Figure 5.4, the right vertical axis tracks the number of active ONUs versus the distance between initial placements of ONUs. In Scenario 5, eight active ONUs result in a power consumption of 3379 W (shown in stripes Figure 5.4), thus Scenario 1 where every (*x*, *y*) coordinate is a possible location for an ONU is the most energy efficient. Which justifies the more possible locations available for ONUs, the fewer number of active ONUs are required and minimum power is consumed. Figures 5.5a and 5.5b show that an increase in active ONUs will result in increased power for transmission of traffic. The BSs that are further away from the nearest active ONU will require their own ONU, resulting in additional transmission and bootstrap power. In Figure 5.5b, the BS at location (12, 1.5) is beyond the transmission distance of ONU9, hence ONU8 was activated to meet the traffic demand of that BS.

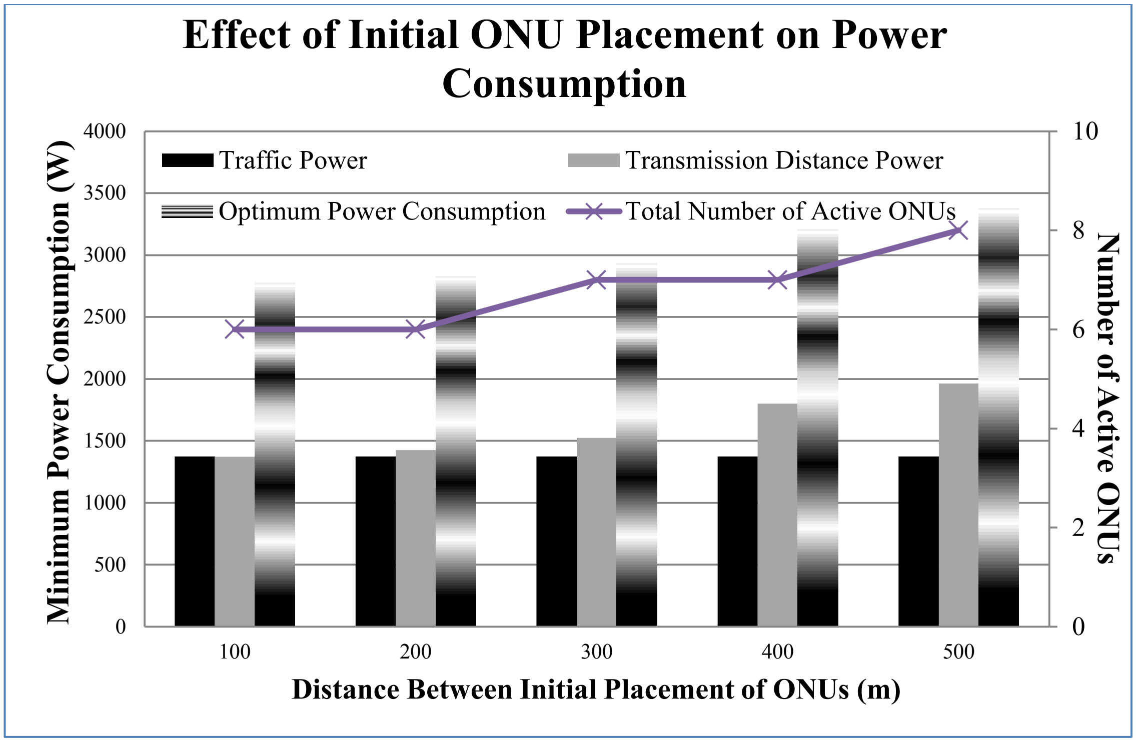

Figure 5.4: Minimum power consumption and total number of active ONUs vs. initial placement of ONUs

Table 5.1: ONU placement scenario results

Scenario	**Minimum Power Consumption (W)**	**Number of Initial Possible Locations for ONU**	**Number of Active ONUs**	**Traffic Power Component (W)**	**Transmission Distance Power Component (W)**
Scenario 1 (100m)	2776	289	6	1375	1371
Scenario 2 (200m)	2830	81	6	1375	1425
Scenario 3 (300m)	2933	36	7	1375	1523
Scenario 4 (400m)	3210	25	7	1375	1800
Scenario 5 (500m)	3379	16	8	1375	1964

Figure 5.5a: Optimum ONU placements for Scenario 1

Figure 5.5b: Optimum ONU placements for Scenario 5

5.2 Effect of ONU Transmission Distance on Power Consumption

There is a trade-off to last-mile reach of an ONU. The increase in transmission distance power is traded for the benefit of having fewer active ONUs. In this section we study the effect of ONU transmission distance on power consumption. We completed simulations for ONU transmission distance T_k from 200 m to 1 km in increments of 100 m. We place the initial ONU locations 100 m apart from one another, at every (*x, y*) coordinate where x and y are 0, 1, 2… Table 5.2 shows the effect of transmission distances of ONUs on total power consumption. Our inputs to the system are as follows: $P = 5W, R_i = 100m,\ \lambda_i = 100Mbps$, $J' = 1Gbps$,$W = 10$ and $I = 5dB$. Our power formulation consists of three power components: the bootstrap power of ONUs, the power required to handle the traffic and the power to transmit between BSs and ONUs. The traffic power component is measured through the sum of λ_i for all BSs connected to their active ONU, with the transmission distance power component measured by D_{ik} from BS_i to ONU_k. In another set of simulations we ignore the transmission distance and measure the power solely as a function of traffic power consumption as described before. We do this by replacing the original formulation (4.1) with (4.2). In (4.2), we remove D_{ik} and leave the dynamic component of the power formulation to be dependent on traffic rates. In Baliga *et al.*, the values for power consumption of a single bit ranged from $100nJ/bit$ to $1000nJ/bit$ [7]. The value for α as our power coefficient was found using median value method as we had done for β. We set α with the value of $550nJ/bit$, we ran simulations for the range of power coefficients of $100nJ/bit$ to $1000nJ/bit$. This resulted in a linear graph, therefore we used the median value from this result to obtain α. We model this modified formulation with the same conditions as our original formulation and achieve the traffic power component of 1375 W for all transmission distances. The model is a homogeneous network, thus $\lambda_i = 100Mbps$ for all BSs. The number of active ONU start-ups is the varying factor for power consumption in (4.2). We use these values to determine our transmission distance power component. The difference between formulations (4.1) and (4.2) is displayed under the transmission distance power component (Table 5.2; Figure 5.6). Due to network dynamics our results are a display of a rough estimate in transmission distance power. In section 5.1, the power consumption increased simultaneously with the number of active ONUs for a fixed value of T_k. However, in this section T_k varies, and we show in Figure 5.7 that the power consumption is primarily dependent on transmission distance power. This is justified from Figure 5.7, the shape of the minimum power consumption follows the shape of transmission distance power in Figure 5.6. Initially, the power required to support the traffic is larger than the transmission power. However, as the transmission distance increases, we notice its dominance on power consumption. Figure 5.6 shows the ONU bootstrap power to be negligible, this is because the power required to start up an ONU and its components is small. The trade-off for fewer active ONUs is shown in Figure 5.7, as the transmission distance increases the number of active ONUs decrease. Simultaneously the minimum power consumption increases.

Table 5.2: Results of the effect of ONU transmission distance on power consumption

Transmission Distance (meters)	Minimum Power Consumption (W)	Number of Active ONUs	ONU Bootstrap Power (W)	Traffic Power Component (W)	Transmission Distance Power Component (W)
200	2054	10	50	1375	629
300	2539	7	35	1375	1129
400	2799	6	30	1375	1394
500	2835	6	30	1375	1430
600	3047	5	25	1375	1647
700	3075	5	25	1375	1675
800	3105	5	25	1375	1705
900	3111	5	25	1375	1711
1000	3118	5	25	1375	1718

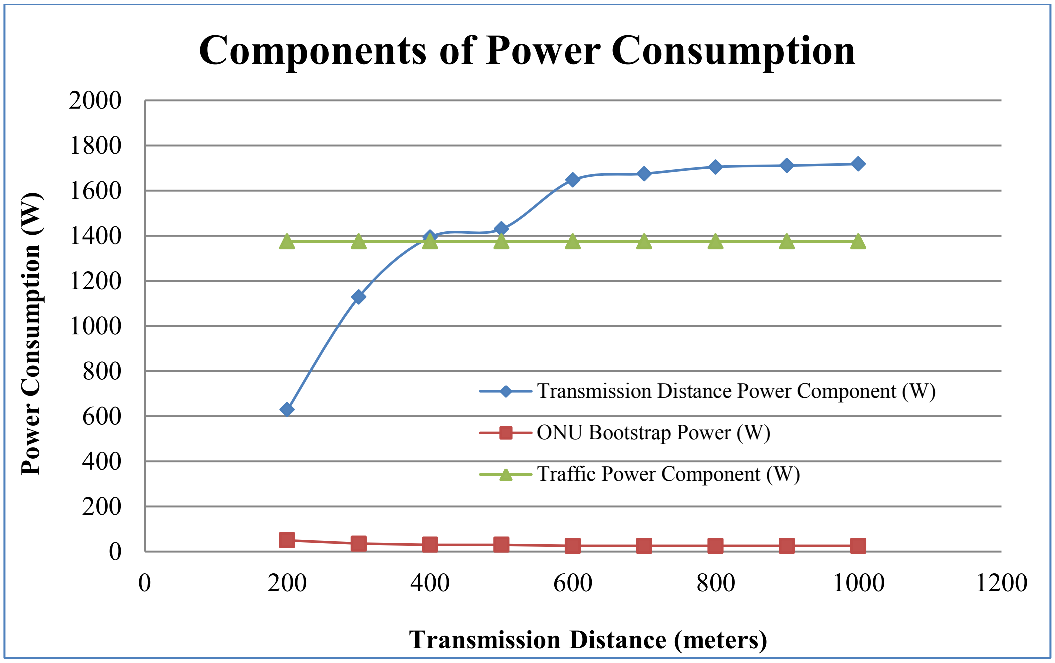

Figure 5.6: Components of power consumption

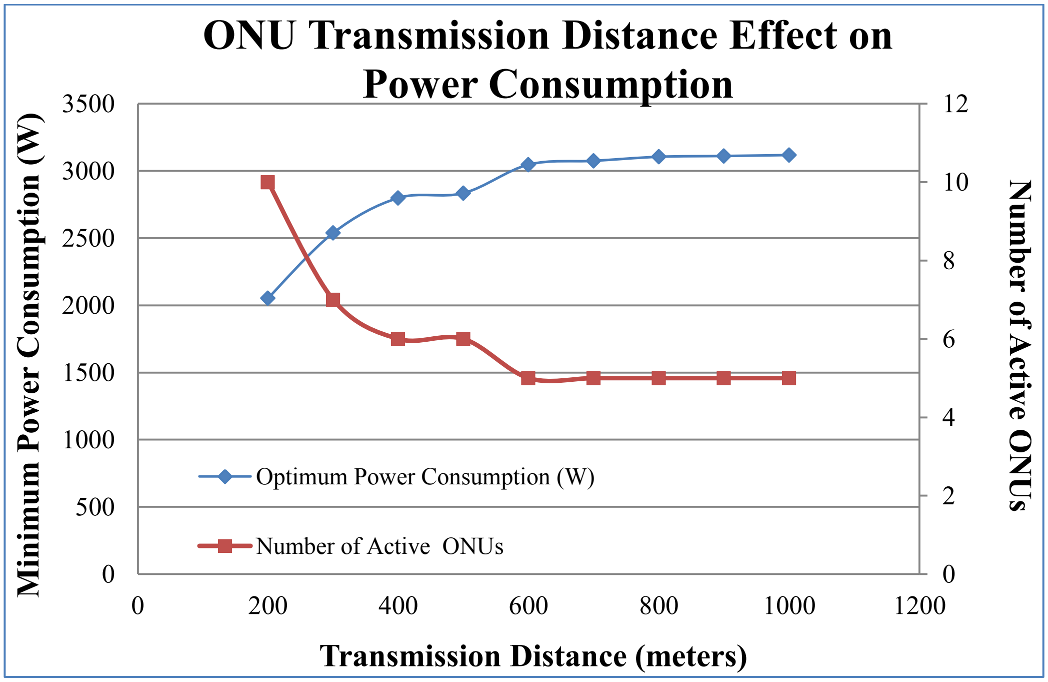

Figure 5.7: ONU transmission distance effect on power consumption

5.3 Effect of Number of Base Stations on Power Consumption

Next we investigate the effect of number of base stations on the power consumption. We initially start the network with 10 BSs distributed throughout the map of SFNet. We then expand the network in increments of 10 BSs, until we reach a maximum of 50 BSs, as shown in Figure 5.8. The locations for ONUs will be in every (*x, y*) coordinate, thus 289 initial possible locations are available. Our inputs to the system are as follows: $P = 5W, R_i = 100m, \lambda_i = 100Mbps$, $T_k = 400m, J' = 1Gbps$, $W = 10$ and $I = 5dB$. Table 5.3 shows the increase in the number of active ONUs is dependent on the number of BSs in SFNet. Since each ONU can support at most 10 BSs due to ONU capacity limitations, we observe that as the number of BSs increase our algorithm will assign the BSs to the ONUs to achieve the best ONU placement locations and minimum power consumption.

Figure 5.8: SFNet with 50 BSs distributed throughout the area

Figure 5.9 presents the power consumption of the power components listed from Table 5.3. The total number of active ONUs (solid line with a cross at each data point) linearly increases as a function of the BSs increasing. Dominance is not displayed between the traffic and transmission distance power components. This is mainly due to the total traffic and the transmission distance between the BSs and ONUs vary in each simulation, as the number of BSs increase in the network. A simulation was completed to model 60 BSs, however the interference threshold was surpassed. No feasible solution was available with our inputs and constraints using 60 or more BSs, but the model function was not impeded below this level.

Table 5.3: Results of the effect of increasing the number of BSs

Number of BSs	Minimum Power Consumption (W)	Number of Active ONUs	ONU Bootstrap Power (W)	Traffic Power Component (W)	Transmission Distance Power Component (W)
10	1060	3	15	550	495
20	2407	5	25	1100	1282
30	3745	6	30	1650	2065
40	4737	7	35	2200	2502
50	5765	9	45	2750	2970

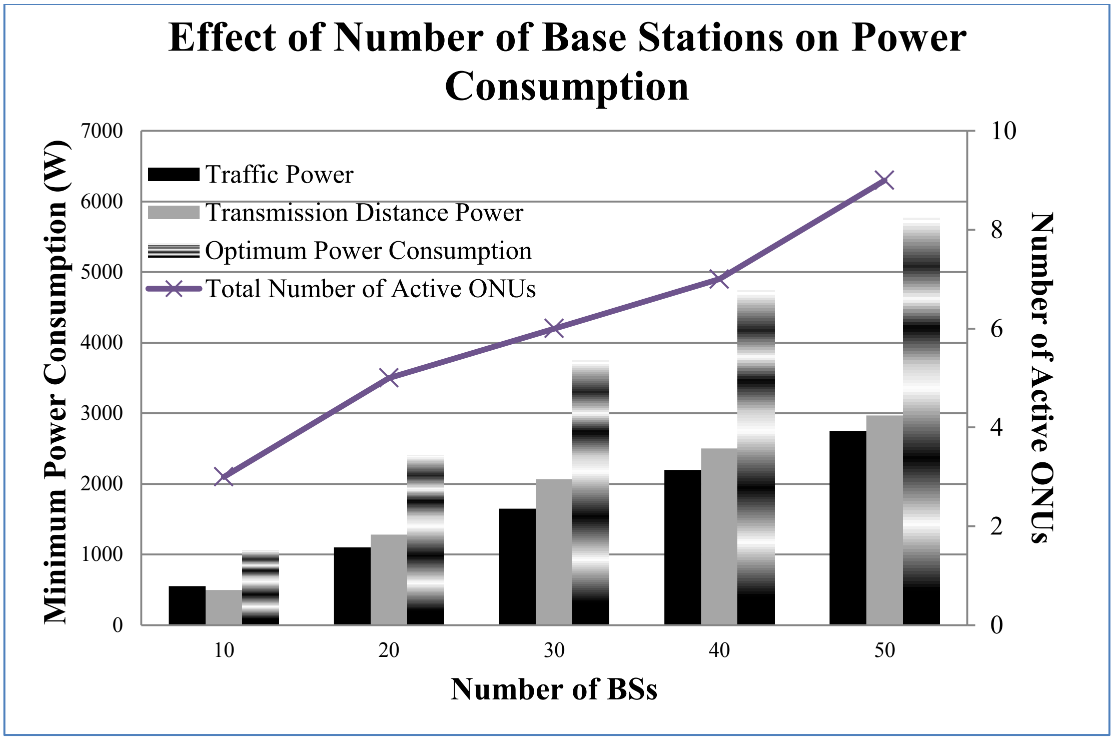

Figure 5.9: Minimum power consumption and number of active ONU dependent on the number of BS in SFNet

5.4 Effect of Channel Reuse Power Consumption using Cell Structures

The simulations presented so far have all been assigned channels randomly. Here we examine how the simulation will behave using predetermined channel assignments through Channel Reuse Method (CRM), detailed in Section 3.2. We also develop a heuristic for the initial placements of ONUs being placed in the middle of a cell. The heuristic for the initial placements of ONUs is a modification of our original (*x, y*) grid, we instead use hexagonal shaped cell structures. We take SFNet and design it such that there are 93 cells with the center of each cell serving as an initial possible location for an ONU (refer to Figure 5.2). If a channel is assigned in one cell it cannot be assigned to the six cells surrounding it. The CRM reuses seven channels throughout the network based on cell structures. We set T_k to 300 m, permitting connection to all neighbouring cells to form a cluster of seven cells (the center cell where the ONU is located and the six cells that are adjacent to it) [45]. When an ONU is initialized for service activation to its assigned BSs, only BSs that are within the ONU cluster and transmission distance can be connected. Referring back to the channel reuse distance equation and channel reuse factor D and k are considered for CRM. The radius of a cell from our simulation is 100 m and a cluster consists of 7 cells, the reuse distance D will have to be greater than 458.26 m and the 6 cells surrounding the cell channel will be the reuse factor k. A channel cannot be reused within those 6 cells, it can only be reused beyond the 458.26 m distance.

In Figure 5.10a we simulate CRM and in Figure 5.10b we simulate random channel assignment method. From these two figures we can see how the network will communicate between BSs and ONUs using our heuristic approach of cell structure instead of a grid structure. In Figure 5.10a, the cells have channels that are assigned to them, therefore if a BS is within that cell, the channel is assigned to that BS. In Figure 5.10b, the cells do not have predetermined channels. The channels are randomly assigned to the cells, if a BS is within a cell it is assigned the channel of that cell. Both Figures have an initial possible location for an ONU at every center of a cell, 93 possible locations (Figure 5.2). When a BS falls in between two cell transmission radiuses, the selected channel will be the one that is not in use by another BS connected to the nearest active ONU. Our inputs to the system are: $P = 5W, R_i = 100\text{m}$, $\lambda_i = 100Mbps$, $T_k = 300\text{m}, J' = 1Gbps, W = 7$ and $I = 5dB$. In CRM, minimum power consumption of 2338 W is consumed, while in random channel assignment the minimum power consumption is 2472 W. Intuitively, we expect that random channel assignments are not efficient in network planning, but that is not the case. With 93 initial possible ONU locations, in both instances eight ONUs are active, with only a slight difference in transmission distance power between CRM and random channel assignment. Although the power consumption is not the same in both methods, and is slightly different, we cannot conclude that random channel assignments are efficient. However we can conclude that both methods result in a minimum power consumption with a minimum number of active ONUs. Other channel allocation schemes will benefit this model and could potentially provide better energy efficiency. A disadvantage of CRM is its inability to support an increased number of BSs. For example, if there were two BSs in one cell, a nearby ONU will be activated to support the second BS in that cell, further increasing transmission distance power and bootstrap power.

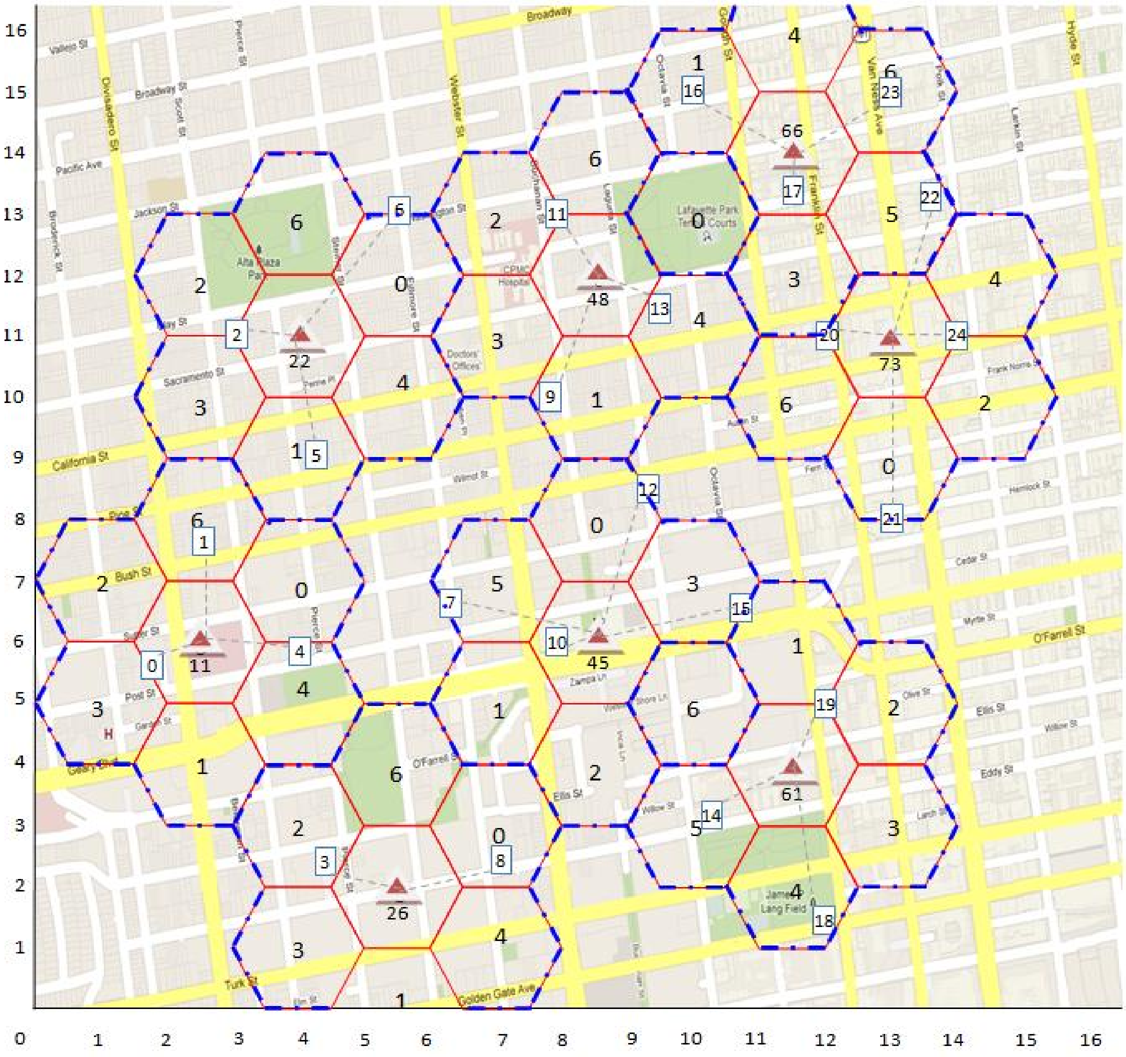

Figure 5.10a: Optimum cell structure using seven CRM

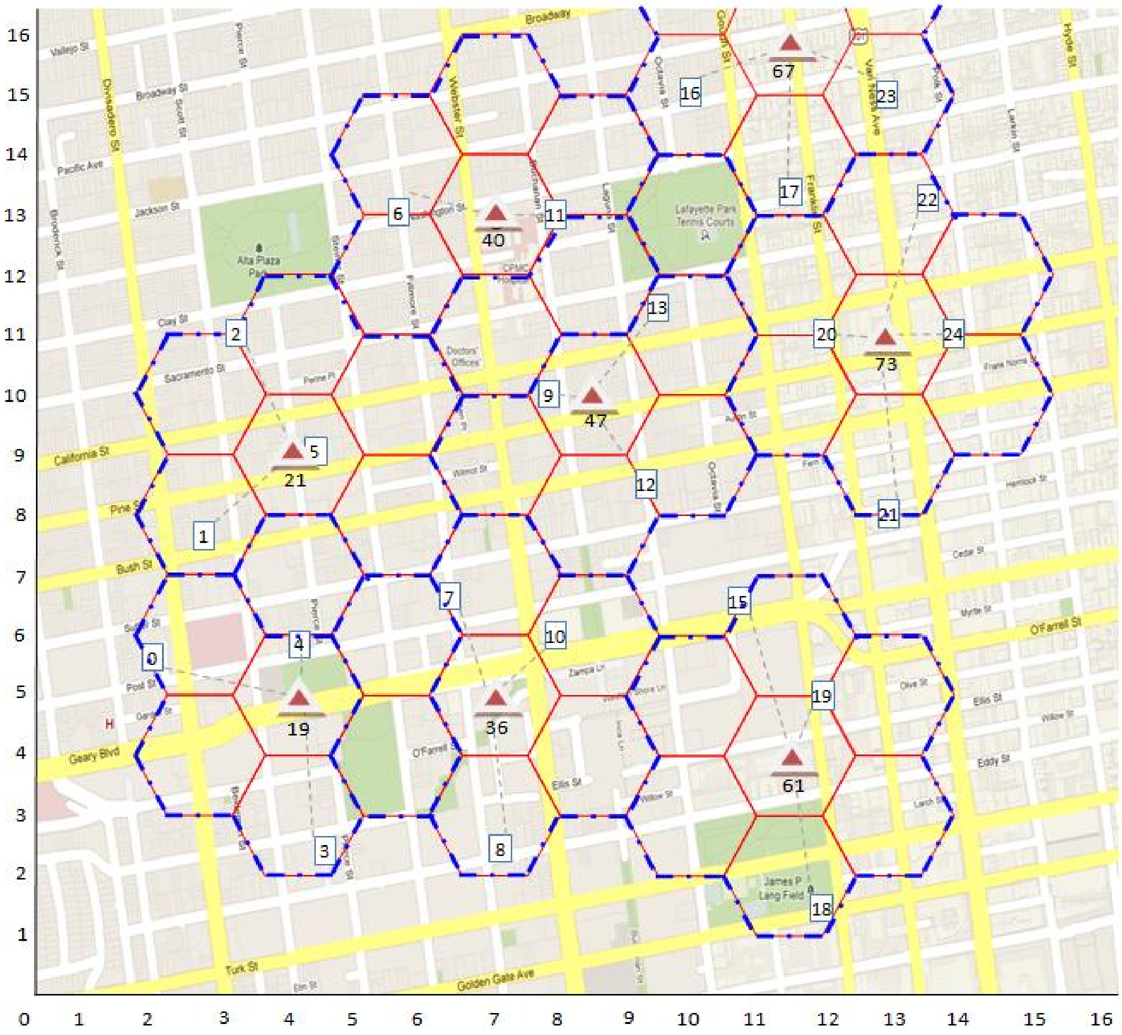

Figure 5.10b: Optimum cell structure using seven channels randomly

Chapter 6

Conclusion and Future Work

Recent interest in green networking is the result in part to rising energy costs and an impetus to meet the requirements of the Copenhagen Accord. In this thesis we have introduced novel optical access networks such as passive optical networks, Ethernet over fibre, Radio Frequency PON also known as RFoG (radio frequency over glass) and free space optical networks. We also introduced wireless access network basics and technologies such as Wi-Fi, WiMAX, and LTE. These introductions had led to the core topic of this thesis: Integrated Wireless Optical Access Networks. We discuss the architecture and research issues of the integration of wireless and optical technologies. We then select a research issue for the placement of optical network units and apply this toward the global aim of greening of the network. We elaborate on work completed in ONU placement algorithms to improve the energy efficiency, work that to the best of our knowledge has not be done previously. The algorithm aims to find a minimal value in power consumption while obtaining prime locations to place the minimum number of actives ONUs. The algorithm uses two formulations, both of which measure power consumption at the network component as the sum of a constant (static) part per start-up (bootstrap power) and a dynamic part during equipment operation.

The first formulation models the dynamic component as the product of the transmission distance from BSs to ONUs and the rate of uplink traffic arriving at the ONUs from the BSs. The second formulation models the dynamic component as a function of the rate of uplink traffic arriving at the ONUs from the BSs. An important observation is made by measuring the difference between the solution to the first and second formulations. The total network power consumption is more highly dependent on the transmission distance and less dependent on traffic rates. The formulations held valid to all conditions and constraints set on the network under all simulations. We used the following constraints for our network: channel assignment, ONU installation, network capacity and signal quality constraints. It is important to measure signal quality, as this will maintain a reliable service connection to all users and BSs. This is achieved by incorporating carrier to interference ratio and co-channel interference into our model.

The minimization of power consumption at all ONUs is completed using an in-house simulation on the CPLEX optimization studio. These simulations are tested for various effects on power consumption, such as the effects of initial placements of ONUs, ONU transmission distances, increases in the number of BSs in the network and our heuristic method for channel assignments. We use channel reuse method with cell structures in comparison to our random channel assignment approach. For the initial ONU placement results, we conclude that the greater the number of initial possible ONU locations, the lower the minimum power consumption. Regarding the effects of ONU transmission distance on power consumption, we conclude that power consumption is primarily dependent on the transmission distance and less dependent on traffic rates. We conclude that the minimum power consumption is also dependent on the number of BSs in the network. However, with our inputs we can only support up to 50 BSs without voiding the signal quality constraint. Finally, for the heuristic channel reuse method’s effect on power consumption, we verified that our random channel assignment method is acceptable in comparison to CRM. In conclusion, the transmission distance power gradually surpasses the traffic rate power. Moreover, the minimum power consumption is affected by the transmission distance required to receive traffic from the BSs more heavily than the power required to support traffic received from the BSs.

With respect to our research, in the future there are several related works that can be addressed. We could focus on alternative placement algorithms, or further develop our current algorithm to incorporate downlink transmission from ONUs to BSs. This can be completed through modifications in the constraints, especially our signal quality constraint and co-channel interference equation to consider ONU level interferences. The algorithm can be further refined by taking advantage of channel assignment algorithms to assign channels in a more sophisticated manner. In CRM, one can investigate the use of dynamic channel allocations or hybrid channel allocation schemes. By doing so, an ONU will have the capability of supporting a greater number of BSs, further reducing the number of active ONUs in the network. Furthermore, a test on the Canadian based optical networks, such as Ontario research and innovation optical network (ORION) can be conducted with their inputs and data values.

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Chapter 7 Appendix

IBM ILOG CPLEX Optimization Studio, referred more simply as CPLEX is an optimization tool that solves integer programming, mixed integer programming and quadratic programming problems. CPLEX is capable of solving very large linear programming problems using either primal or dual options of the simplex method or the barrier interior point method, convex and non-convex quadratic programming problems, and convex quadratically constrained problems. CPLEX Optimizer has an extra feature called Concert Technology, which interfaces C++, C#, and Java programming languages. It also has a python language interface built on the C interface. CPLEX can also be branched out to be connected to Microsoft Excel to output results, and MATLAB. There are many advantages of using CPLEX: automatic and dynamic algorithm parameter controls, fast automatic restarts, variety of problem modifications, a wide variety of input and output options, and also provides post solution information and analysis. Working with CPLEX was difficult to learn, however once accustomed to the tool CPLEX is efficient in which it saves computation timing and resources.

Below is a copy of the in-house source code.

```
/*********************************************
 * OPL 12.3 Model
 * Author: Karthick
 * Creation Date: Oct 10, 2011 at 1:32:18 PM
 *********************************************/
 /*--------------------------------------------------------*/

int Fix_BS_Locations = ...; //data file separated
range BaseStation = 0 .. Fix_BS_Locations-1;
      //Set of fixed BS locations at i (L)
int Pos_ONU_Locations = ...;
range ONU = 0 .. Pos_ONU_Locations-1;
      //Set of possible ONU locations at k (O)
/*-----------------------Setting Random Seed--------------------*/
int mySeed;
execute{
      var now = new Date();
      mySeed = Opl.srand(Math.round(now.getTime()/1000));
}
int b = srand(mySeed);
float r[i in BaseStation] = (rand(1000))/1000;
float e[i in BaseStation] = (rand(1000))/1000;
int l = rand(16);
//int m = rand(16);
execute {
 writeln (r);
 writeln (b);
 writeln (l);
 writeln (e);}

 //Location for BS & ONU using x,y axis from a grid pattern
tuple xyaxis{
  float x;
  float y;}

xyaxis Baxis[BaseStation] = ...;
xyaxis Oaxis[ONU] = ...;

/* --------------------Alternate way to write the grid for lcoations---
------

int locationxy = ...;
range location = 0 .. locationxy-1;
float Baxis[BaseStation][location] = ...;
float Oaxis[ONU][location] = ...;
[[0,0], [0,3], [0,4], [1,0], [1,2], [1,4], [2,1], [2,3], [2,4],
         [3,2], [3,3], [4,0], [4,1], [4,3], [4,4]];

[[0,0], [0,1], [0,2], [0,3], [0,4], [1,0], [1,1], [1,2], [1,3],
         [1,4], [2,0], [2,1], [2,2], [2,3], [2,4], [3,0], [3,1], [3,2],
         [3,3], [3,4], [4,0], [4,1], [4,2], [4,3], [4,4]]; */
int one = 1;
int NbChannels = ...;
```

```
range Channels = 0 .. NbChannels-1;
      //Set of available wireless channels at c(F)
int UB_Channels = ...;
      //UB on number of channels assigned to a ONU (A)
int BSTrans[BaseStation] = ...;
      //Set of BS transmission radiuses
int UB_ONUCap = ...;
      //UB for ONU Capacity (J`)
int Up_Data[BaseStation] = ...;
      //Average Upstream traffic rate demand of BS@location i
float CI_Ratio= ...;
      //Carrier Interference Ratio (I)
int BigNb = ...;
      //Arbitrarily large number (G)
int Power_Start = ...;
      //Initial power needed to turn on ONU/Gateway (P)
float Power_Traffic = ...;
      //Coefficient to translate traffic into power
int Max_ONU = ...;
      //Maximum number of ONUs
float ONUTrans[ONU] = ...;
            //ONU Transmission radius
float BS_ONU_d[i in BaseStation][k in ONU] =
            sqrt((Baxis[i].x - Oaxis[k].x)^2 + (Baxis[i].y -
      Oaxis[k].y)^2); //Distance b/w BS@i to ONU@k

float BS_BS_d[i in BaseStation][j in BaseStation] =
            sqrt((Baxis[i].x - Baxis[j].x)^2 + (Baxis[i].y -
      Baxis[j].y)^2); //Distance b/w BS@i to BS@j



/*--------------------------------------------------------------*/
dvar boolean Installed[ONU];
      //1, if ONU is installed at k, otherwise 0 (Uk)
dvar boolean Connection[BaseStation][ONU];
      //1, if ONU at k is connected to BS at i, otherwise 0 (Zik)
dvar boolean BSChannel[BaseStation][Channels];
      //1, if channel c is assigned to BS at i, otherwise 0 (Xic)
dvar boolean On[ONU];
      //1, if ONU at k is powered on, otherwise 0 (Yk)
dvar int ONUCap[ONU];
      //capacity of ONU at k (Jk)

/*------------------------Interference Factor--------------------*/
dexpr float Interference[i in BaseStation][j in BaseStation] =
(BSTrans[j]/(BS_BS_d[i][j]))^4;

/*--------------------Objective---------------------------------*/
minimize
  sum(k in ONU)
    On[k]*Power_Start +
  sum(k in ONU)
```

```
    sum(i in BaseStation)
      Connection[i][k]*Up_Data[i]*Power_Traffic;
/*-----------------------Channel Assignment---------------------*/
subject to {
    forall(i in BaseStation){
            if(0 <= r[i] < 0.1){
              BSChannel[i][0] == 1;}
            else if(0.1 <= r[i] < 0.2){
              BSChannel[i][1] == 1;}
            else if(0.2 <= r[i] < 0.3){
              BSChannel[i][2] == 1;}
            else if(0.3 <= r[i] < 0.4){
              BSChannel[i][3] == 1;}
            else if(0.4 <= r[i] < 0.5){
              BSChannel[i][4] == 1;}
            else if(0.5 <= r[i] < 0.6){
              BSChannel[i][5] == 1;}
            else  if(0.6 <= r[i] < 0.7){
              BSChannel[i][6] == 1;}
            else if(0.7 <= r[i] < 0.8){
              BSChannel[i][7] == 1;}
            else if(0.8 <= r[i] < 0.9){
              BSChannel[i][8] == 1;}
            else if(0.9 <= r[i] < 1){
              BSChannel[i][9] == 1;}
            }



  forall(i in BaseStation)
UB_Channelct:
      sum(c in Channels)
        BSChannel[i][c] == one;
//if you want to adjust the total number of channels to be assigned
//to a BS replace one with another number


forall(c in Channels){
forall(k in ONU){
    ChannelUsedOnce:
    sum(i in BaseStation)(Connection[i][k]*BSChannel[i][c]) <= one;}}

forall(k in ONU)
ONU_Channel_Capct:
  (sum(i in BaseStation)Connection[i][k]) <= On[k]*UB_Channels;




/*-----------Capacity and Traffic for BS and ONU-----------------*/
  forall(k in ONU)
BS_traffic_Capct:
    sum(i in BaseStation)
```

```
      Up_Data[i]*Connection[i][k] == ONUCap[k];
  forall(k in ONU)
Inequalityct:
  ONUCap[k] <= UB_ONUCap*On[k];
  forall(k in ONU)
Inequalityct2:
  ONUCap[k] >= 0;

/*----------------------Signal Quality---------------------------*/

  forall(i,j in BaseStation: i!=j)
    Interference[i][j] >= 0;

  forall(i in BaseStation, c in Channels)
interferencect:
  (sum(j in BaseStation: j!=i)
    (Interference[i][j]*BSChannel[j][c])) <= (BigNb + (1/CI_Ratio -
BigNb)*BSChannel[i][c]);
/*-----------------------ONU Installations----------------------*/
  forall (i in BaseStation){
    forall (k in ONU){
    Connection[i][k]*BS_ONU_d[i][k] <= ONUTrans[k];
  }
}
   forall (i in BaseStation)
BS_one_ONUct:
      sum(k in ONU)
              Connection[i][k] == 1;

  forall(i in BaseStation, k in ONU)
Connection_ONUct:
    Connection[i][k] <= On[k];
  forall (k in ONU)
On_if_Installedct:
    On[k] <= Installed[k];
Max_ONUct:
  sum (k in ONU)
    Installed[k] <= Max_ONU;

}
```