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WIRELESS INDUSTRIAL AUTOMATION

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THROUGHPUT IMPROVEMENT AND COMPARATIVE PERFORMANCE ANALYSIS OF INTEGRATED NETWORKS

Master’s thesis for the degree of Master of Science in Technology that has been submitted for inspection, Vaasa 28 June, 2020.

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FOREWORD

First, I thank the Lord Jesus Christ, whose strength has enabled me to persevere in the completion of this thesis.

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Finally but not least, my fiancee Nikolett Gerencser, whose never-ending encouragement was great succour in the completion of this thesis.

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LIST OF SYMBOLS AND ABBREVIATIONS

<	Less Than
>	Greater Than
µs	Microsecond
CGAR	Compound Annual Growth Rate
E2E	End to end
E-UTRAN	Universal Terrestrial Network
3GPP	Third Partnership Project
4G	Fourth Generation
HTTP	Hypertext Transfer Protocol
LTE	Long Term Evolution
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
OFDMA	Orthogonal Division Multiple Access
MIMO	Multiple Input Multiple Output
OFDM	Orthogonal Frequency Division Multiplexing
PHY	Physical Layer
QoS	Quality of Service
SCF	Small Cell Forum
SCBSs	Small Cell Base Stations
SSs	Subscriber Stations
UMTS	Universal Mobile Telecommunication
WLAN	Wireless Local Area Network

WiMAX	World Wide Interoperability for Microwave Access
SC-FDMA	Single Carrier Multiple Access
EPC	Evolved Packet Core
DFT	Discrete Fourier Transform
ENodeB	Evolved Node B
MME	Mobility Management Entity
HSS	Home Subscriber Server
S-GW	Serving Gateway
PDN	Packet Data Network
APN	Access Point Name
OPNET	Optimized Networks Engineering Tool
MIMO	Multiple Input Multiple Output
GGSN	Gateway GPRS Support Node
SGGN	Serving GPRS Support Node
PCRF	Policy and Charging Rules Function
HetNet	Heterogenous Network
Tx	Transmitted Power
SMTP	Simple Mail Transfer Protocol
POP	Post Office Protocol
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
QAM	Quadrature Amplitude Modulation
DL	Downlink
UL	Uplink
SC-FDMA	Single Carrier Multiple Access

DSSS	Direct Sequence Spread Spectrum
CDMA	Code Division Multiple Access
BSs	Base Stations
BDP	Bandwidth-Delay Product
HHO	Hard Handover
MDHO	Macro Handover Diversity
FBSS	Fast Base Station Switching

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ABSTRACT

The demand for high-speed communication continue to increase significantly. Industry forecasts have shown that future data services would contribute to rapid growth in data traffic, with most of this traffic primarily indoors and at hotspots locations. Thus, the deployment and integration of small cell base stations (SCBSs) with Wireless Local Area Network (WLAN) or Wi-Fi is viewed as a critical solution to offload traffic, maximize coverage and boost future wireless systems capacity.

This thesis reviews the existing network of WLAN, Long Term Evolution (LTE) and Worldwide Interoperability for Microwave Access (WiMAX). Tight and Loosely coupled integration of these networks is studied.

More specifically, the introduction of small cell (SC) in loosely coupled Wi-Fi /WiMAX and Wi-Fi/LTE are proposed. These designs are tested in real-time user experience applications consisting of video conferencing, hypertext transfer protocol (HTTP) and email using industrial simulation software, Riverbed Modeler 18.7.

Quality of service parameters was used to analyze these networks. It was found that the throughput of loosely coupled Wi-Fi/WiMAX network can be optimized by small cell. The loosely coupled architecture of Wi-Fi/WiMAX small cell outperforms that of Wi-Fi/LTE small cell. The loosely coupled independently deployed network of Wi-Fi/LTE small cell performs better than the Wi-Fi network. The Wi-Fi/LTE small cell network achieved a substantial rise in downlink throughput in a network consisting of only video conferencing subscriber stations.

KEYWORDS: Email, HTTP, Loose Coupling**,** LTE, Small Cell, Video Conferencing, Wi-Fi

1 INTRODUCTION

Annual global mobile data traffic will reach nearly one zettabyte by the end of 2022. A zettabyte corresponds to 1 trillion gigabytes of data. Thus, when traffic demand increases significantly, and millions of new applications become available on the network, there must be changes in devices, improvement in throughput and quality of service. (Technology Vision 2020 – Nokia Network, 2015).

Driven by the flourishing ecosystem, small cells and Wi-Fi network deployments are expected to account for almost $352 trillion in revenues from mobile data services by the end of 2020, while total heterogeneous network (HetNet) infrastructure spending is expected to reach $42 annually over the same time frame. (The HetNet Bible. Small cell and carrier Wi-Fi – SNT Telecomm & IT, 2013).

Additionally, the Small Cell Forum (SCF) forecasts new outdoor small cell deployments annual growth at about 36 percent between 2015 to 2025 to be 22-fold higher than 2015. (Small Cell Forum Unveils Operator Research Showing Accelerating Densification and Enterprise Deployments on Road to 5G, 2017). In 2017, 54% of total mobile data traffic was offloaded via Wi-Fi or femtocell to a fixed network.

It has been estimated that most of this mobile data traffic will be composed of video, hypertext transfer protocol application (HTTP) and email. Thus, HTTP application and email are projected to rise by more than 28% from 2017 until 2022. Globally, IP video traffic will constitute 82 percent of all IP traffic by 2022 in comparison to 75 percent in 2017. Figure 1 provides a projection of mobile data growth from the year 2017-2022. It is expected that overall mobile data traffic will increase in 2022, a seven-fold increase over 2017 to 77 exabytes per month and thus, mobile data will increase from 2017 to 2022 at Compound Annual Growth Rate (CAGR) of 46%. (Forecasts and Trends 2017-2022 white paper–Cisco Visual Networking Index, 2019). Although advancements in cellular technology have resulted in increased performance, meeting the demand for high performance, low-cost services remain enormously challenging. Therefore, for operators to remain on the competitive edge, and to deliver better coverage and more capacity, there must be an intense consideration for modification of existing mobile architecture. (Technology Vision 2020 – Nokia Network, 2015).

Figure 1. Mobile data growth forecast from 2017 to 2022. (Forecasts and Trends 2017-2022 white paper – Cisco Visual Networking Index, 2019).

Existing network of Wi-Fi, Long Term Evolution (LTE) and Worldwide Interoperability for Microwave Access (WiMAX) must be integrated. The integrated network can exist in the form of Wi-Fi/WiMAX and Wi-Fi/LTE. These respective networks can either be integrated as loose or tight coupling architecture**.** Small cell base stations (SCBSs) has proven to maximize capacity and throughput when they coexist with a macro BSs. By the introduction of SCBSs into these integrated networks, throughput and capacity of the networks can be highly optimized. (Rising to Meet the 1000x Mobile Data Challenge – Qualcomm: Wireless Technology and Innovation, 2012).

The Long Term Evolution (LTE), also known as the E-UTRAN (Evolved-Universal Terrestrial Access Network) was developed in the release 8 of the 3rd Generation Partnership Project (3GPP). The main requirement was flexibility in bandwidth and frequency, high spectral efficiency and data rates (Nohrborg, 2018). WiMAX is based on the standard IEEE 802.16 family and meets all personal broad specifications. WiMAX is an all-IP, data-centered OFDMA based technology suitable for wireless 4G service delivery. WiMAX is currently being used by operators around the world. WiMAX has application in devices like USB dongles, Wi-Fi systems, tablets, and mobile phones. (WiMAX 4G Mobile –WiMAX forum, 2019).

Wi-Fi is the wireless communication brand name which uses radiofrequency to transmit data via air. Its coverage area is from about 50-100 m (Sourangsu & Rahul, 2013). Wi-Fi must be integrated with WiMAX or LTE having a broader coverage to expand its coverage and enhance capacity. In network integration, the network of Wi-Fi, WiMAX, and LTE coexist with each other, thereby achieving higher capacity, greater bit rates, and low network interference (Zhou & Li, 2018). An integrated network of Wi-Fi with LTE and WiMAX are in the form of Wi-Fi/LTE and Wi-Fi/WiMAX. The methods of integration are loose and tight coupling system. (Zhang, et al., 2011).

A converged Wi-Fi/LTE or Wi-Fi/WiMAX solution is desirable to operators. This will make them to take advantage of each technology's relative strengths while downplaying their weakness. Current integration schemes in a heterogeneous network of Wi-Fi/WiMAX and Wi-Fi/LTE allow users to migrate from one network to another or use both radio interfaces simultaneously. A typical web browser client whose network is configured in Wi-Fi/LTE could migrate from LTE to Wi-Fi when Wi-Fi is available. (Ling, et al., 2012).

Small cell base stations (SCBSs) are generally femtocells, picocells, and macrocell bastions of Wi-MAX or LTE. They can coexist with Wi-Fi to form an integrated network. Thus, WiMAX SCBSs can also coexist with LTE SCs. These base stations (BSs) can be deployed in an area where a macro station already existed. (Rising to Meet the 1000x Mobile Data Challenge – Qualcomm: Wireless Technology and Innovation, 2012).

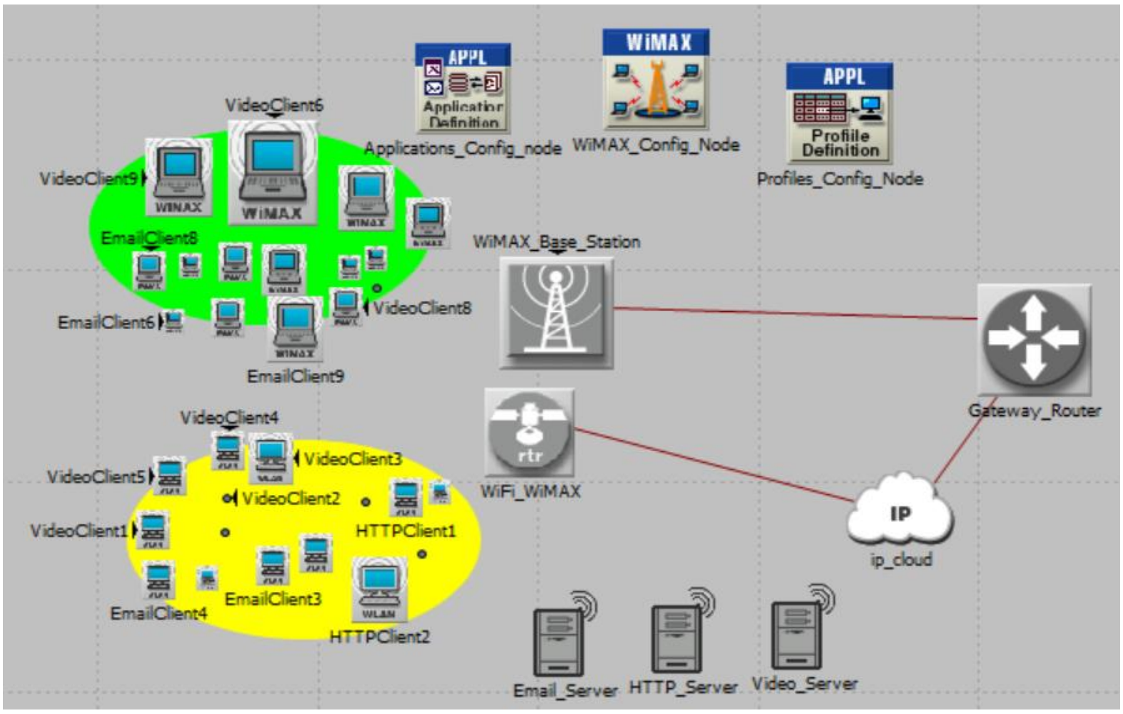


Figure 2. Wi-Fi/WiMAX loose coupling integration.

In Figure 2, a loose coupling architecture was designed. Wi-Fi is integrated with WiMAX network with a single macro BS. In loose coupling architecture, the subscriber wishes to use the same account number, password and service network, receive the same account bill, expand services to the new system and ensure continuity of operation between the various networks. Use of the same accounting and billing system will significantly reduce operating costs, maintenance and hardware costs. The network of Wi-Fi and WiMAX and the Wi-Fi and LTE are independently deployed in loose coupling system. (Zhou & Li, 2018).

1.1 Research contributions

Zhang et al., (2011) proposed the Wi-Fi and LTE small cell integration with both networks sharing the unlicensed spectrum. Thus, Wi-Fi and LTE small cell use the same unlicensed spectrum – 2.4 GHz band without impacting the Wi-Fi system performance. Their results stated that the proposed architecture could substantially increase the capacity of the 4G heterogeneous small cell network while sustaining the quality of service of Wi-Fi systems.

Reem A. H. et al., (2004) proposed an LTE/WiMAX and LTE/Wi-Fi architecture using an IP Multimedia System (IMS) as the merger between the two networks. They compared it with the Universal Mobile Telecommunication Service Network, (UMTS) and WiMAX in UMTS/WiMAX and UMTS/Wi-Fi architecture using tight coupling system. Their results stated that the proposed architecture out-perform the previous one in VOIP application.

Benoubira S. et al., (2011) proposes a new system of loose coupling that interconnects the universal mobile telecommunication system, UMTS and WiMAX without any changes in the existing architecture. They concluded that packet loss rate is minimum in the loose coupling architecture as compared to the tight coupling system.

Huawei tested user experience with LTE SC–based on and Wi-Fi based on 802.11n. The result of the test stated that LTE SC has a better quality of service when compared to Wi-Fi. (LTE SC v.s. Wi-Fi User Experience – Huawei 2013).

Qualcomm, based on their previous research studies, has hypothesized the possibility of enormous capacity increase with SC. They estimated the possibility of getting a 500 times capacity increase when 65 SCs are deployed for every macro cell, and a 1000 times capacity increase when 144 SCs are deployed for every macrocell. (Rising to Meet the (Rising to Meet the 1000x Mobile Data Challenge – Qualcomm: Wireless Technology and Innovation, 2012).

Kalhoro Q. et al., (2010) configure a WiMAX and UMTS macro BS with parameters to model a femtocell network. Comparative analyses were done for Wi-Fi, UMTS and WiMAX femtocell in terms of throughput and delay using the Optimized Network Engineering Tool (OPNET)**.** It was concluded that WiMAX femtocell has the best performance and less delay.

Asim I. and Mohammad N. B., (2017) proved in their researched paper that WiMAX femtocell could optimize throughput. They designed a WiMAX network with a macro BS at 30 km from the network. This was designated as a network without femtocell. In their second test case, WiMAX BS was introduced with the parameters of a femtocell network.

Nithyanandan L. and Parthiban I., (2012) integrated mobile network of WLAN, WiMAX, LTE using the tight and loose coupling. Two methods such as reservation of adjacent bandwidth and relocation of gateways were used to reduce latency. Parameter such as vertical handover delay was used to analyse the networks by locating the mobile SS in a WLAN, LTE and WiMAX coverage area. It has been found that the tightly coupled architecture with gateway relocation has a better performance.

Alcatel-Lucent has announced its Wireless Unified Network strategy in Barcelona Spain in 2015 Mobile World Congress (MWC) (Technology Extends LTE Benefits to the 5GHz Unlicensed Spectrum to Increase Capacity for Mobile Users–Qualcomm, 2015). It combines Wi-Fi uploads and downloads capabilities with LTE enabling increased capacity and providing a more stable and improved quality of mobile voice, data and video experience for SSs in hotspot environments. The approach would allow operators to integrate LTE and Wi-Fi networks into a single unified wireless system for both indoor and outdoor environments. (MWC15: Alcatel-Lucent blends the best of Wi-Fi and LTE to enhance mobile performance–ET Telecom, 2015).

1.2 Research problems

Existing integrated networks of Wi-Fi/WiMAX, Wi-Fi/LTE proposed by previous researchers promise seamless continuity beyond the Wi-Fi network, larger coverage area, and high bandwidth. These integration networks generally comprise of a macro-centric BSs and SSs. Thus, it will be financially inefficient to build adequate integrated networks of this nature with macrocell base stations that will meet the projected exponential demand in data.

The Alcatel-Lucent LTE small cell (unlicensed spectrum) integration with Wi-Fi requires changes in hardware, and this is an additional installation cost to customers. In Asim I. and Mohammad N. B., (2017), the distance of WiMAX macro BS at 30 km is not realistic in a real-life scenario as most WiMAX networks are positioned at less than 5 km from the network. At 30 km distance, the network is almost fully degraded, resulting in poor QoS (What is WiMAX Technology? – WiMAX Forum, 2020).

Moreover, whenever network location is far from the macro BS, the throughput of the network is affected. Thus, the thesis will answer the following questions:

- How can the existing network meet the exponentially rising demand in data?
- To what extent is the throughput and capacity of the system increased as more SCBSs are added to the network?
- What network architecture has the best user experience in terms of an overall analysis of performance metrics?
- To what extent does more use of SCBSs maximize the throughput of the integrated network?

1.3 Objectives of the thesis

The integration of the small cell network of WiMAX and LTE with Wi-Fi in a loosely coupled architecture has never been studied. Thus, the objectives of this thesis are to design a loose coupling architecture of Wi-Fi 802.11ac and integrate the network with WiMAX and LTE. Instead of a network of macro BS, an inexpensive small cell will be designed. By the introduction of a small cell in a loose architecture in an independently deployed scenario or integrated with macro BS, coverage and throughput optimization will be achieved. These integrated networks of Wi-Fi/WiMAX small cell and Wi-Fi/LTE small cell will be tested in real-time user experience applications consisting of Email, HTTP and Video Conferencing. Performance metrics and quality of service parameters are used to comparatively analyze these designs.

The first part of this thesis will highlight in theory the Wi-Fi extensions, the LTE network and WiMAX standards, architecture and deployment models and overview of small cell. Chapter 3 focuses on network integration and performance metrics. Loose and tight coupling architectures are briefly explained. Chapter 4 highlights the design and implementation of the respective network, and Chapter 5 is a summary of the outcome and analysis of the thesis work. Chapter 6 covers the conclusion and future work.

2 OVERVIEW OF WI-FI, LTE AND WIMAX NETWORKS

The main physical parameters of Wi-Fi, WiMAX, and LTE are summarized in Table 1. Some primary physical requirements of IEEE 802.11ac are also described in Table 2. One of the most significant specifications that must be considered is the carrier operating frequency. The IEEE 802.11ac network, the IEEE 802.16 network and LTE are further explained in subsequent sections.

Table 1. Comparison between IEEE 802.11ac, WiMAX and LTE.

Parameters	**IEEE 802.11ac (Wi-Fi)**	**1EEE 802.16e (WiMAX)**	**LTE**
DL/UL peak data rates (Mbps)	1300	45/13	100/50
Carrier frequency (GHz)	2.4	2.3- 3.6	700-2.6
Coverage area (km)	0.150	3.0-5.0	5.0
Duplexing scheme	CDMA/CA	TDD and FDD	TDD and FDD
Access schemes	OFDM/DSSS	OFDM	OFDM

2.1 IEEE 802.11 standard for Wi-Fi networks

The IEEE 802.11 standard version was first released in 1977 and it defined a throughput of 1 or 2 megabits per second (Mbps) and consists of physical layer specifications and Medium Access Control (MAC). The 802.11b is highly reliable, inexpensive and functions within the 2.4 GHz range, having some security drawbacks and is significantly affected by interference from nearby devices. A typical Wi-Fi access point (AP) uses a 30-50 m (indoor) and 100 m (outdoor) omnidirectional antennas. IEEE approved the

802.11ac in a frequency band of 7 Gbps and 7 Gbps maximum data rates far higher than the 802.11n data. Today, office workers are aiming to connect mobile devices with secure access from multiple locations. The necessity for network devices to connect to the internet of things continue to grow significantly, allowing access to workplace equipment such as sensors, thermostats, wireless devices, and cameras. Greater mobility and user-friendly network are the growing need of today' world. (Sourangsu & Rahul, 2012).

Table 2. IEEE 802.11x Standard Family.

IEEE 802.11extensions	802.11g	802.11n	802.11ac
Frequency (GHz)	2.4	2.4 or 5.0	5.0
Data rate (Mbps)	54.0	600.0	1300.0
Modulation	OFDMA	MIMO	

2.1.1 The Wi-Fi and devices

Wi-Fi network is wireless communication brand name that uses wireless radiofrequency to transmit data via air. The 802.11ac–the new Wi-Fi extension, is expected to gain popularity from 2018 to 2023. By 2023, 66.8% of all Wi-Fi terminals will be configured with either 802.11ac or Wi-Fi 5 (Global Internet adoption and devices and connection – Cisco Annual Internet Report, 2020).

Wi-Fi devices provides inexpensive deployment of local area networks. Products with an approved Wi-Fi brand generally indicates that the Wi-Fi devices have been tested and have met IEEE 802.11 safety and interoperability testing requirements. Products with a licensed Wi-Fi brand usually mean that the Wi-Fi products were tested and met the specifications of the IEEE 802.11 interoperability tests. (Certification – Wi-Fi Alliance).

2.1.2 IEEE 802.11ac high data rates

The 802.11ac is an improvement from the 802.11n. The main aim is to deliver higher performance levels in accordance to Gigabit Ethernet networking requirement:

- A high throughput SS experience for data transfer
- An advanced network capable of offering high quality of service (QoS)
- Enhanced utilization of video streaming, and applications with a high bandwidth

IEEE 802.11ac has PHY maximum data rates of 1300 Mbps and operates at a 5 GHz frequency as shown in Table 3 and Figure 4. It uses $3x3$ MIMO as its modulation technique.

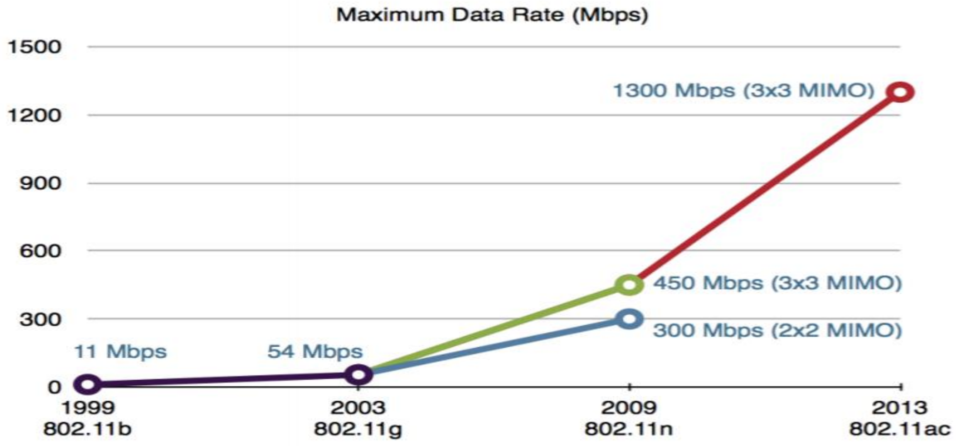


Figure 4. The high data rates of IEEE 802.1lac (802.11ac Migration Guide – Cisco Meraki, Cisco Systems, Inc.).

Table 3 Calculating the 802.11n and 802.11ac speed.

PHY	**Bandwidth (as number of data subcarriers)**	**Numbers of spatial streams**	**Data bits per subcarrier**	**Time per OFDM**
802.11n or 802.11ac	56 (20 MHz)	1 to 4	5/6 x $\log_2$ (64) = 5	3.6 µs (short guard interval)
	108 (40 MHz)			4.6 µs (long guard interval
802.11ac only	234 (80 MHz)	5 to 8	5/6 x $\log_2$(256) = 6.67	Same as above
	2 x 234 (160 MHz)			

Given an 80 MHz bandwidth with the time per OFDM (T_s) of 3.6 µs sent at 256 QAM. The high data rate R_b of the 802.11ac are related by the number of spatial streams (N_s), the number of data subcarrier (N_d), the data bits per subcarrier R and symbol duration or the time per OFDM (T_s) as shown in Figure 4 using the equation 1 and parameters in Table 3. For 256 QAM, the number of messages $M = 256$.

$$R = \frac{5}{6} \text{x}\, log_2 M \;\; where\ log_2 256 = 8\ bit,\ N_s = 3, T_s = 3.6\ us, N_d = 234.$$

$$R_b = \frac{N_d N_s R}{T_s} \tag{1}$$

$$R_b = \frac{234x3x\frac{5}{6}x8}{3.6x10^{-6}} = 1300\ Mbps$$

Thus, the estimated PHY data rate of 1300 Mbps is the data rate of IEEE 802.11ac. (IEEE 802.11ac: The Fifth Generation of Wi-Fi – Cisco technical white paper, 2018)

2.2 IEEE 802.16 standard and network

WiMAX network consists of physical layers, which are responsible for encoding and decoding signals, as well as the transmission and reception of bits. The WiMAX MAC layer which functions as point-to-multipoint protocol is also a part of them WiMAX architecture. (IEEE Standard for Local and Metropolitan Area Networks, Part 16: Air Interface for Fixed Broadband Wireless Access Systems IEEE 802.16 – IEEE Standard 802.16, 2004). It sustains high bandwidth and is therefore capable of serving many users in one channel. Figure 5 shows a simple WiMAX network. It consists of the SSs, the BS, IP cloud, (internet) the server and configuration nodes.

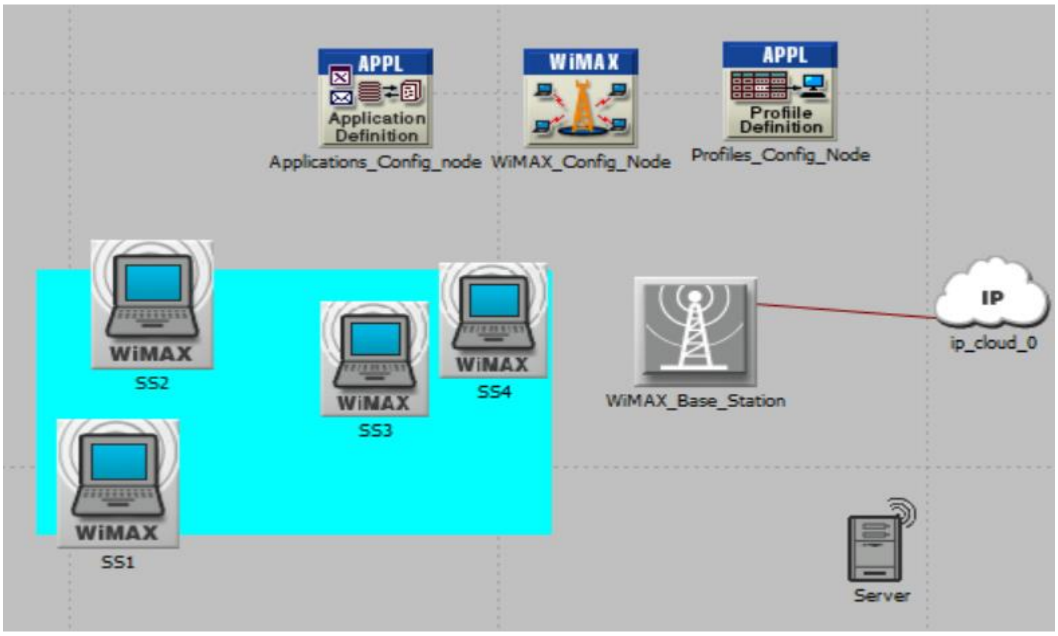


Figure 5. The WiMAX networks.

2.2.1 WiMAX architecture and deployment models

WiMAX architecture is composed of two categories of fixed stations:

- Subscriber Stations (SSs), which serve a residential or business buildings
- Base Stations (BSs), which establish a connection to the public network. It also allows the SS to connect with public network through first-mile access.

The path of communication between the user and base station occurs via two directions:

- The uplink (from SS to BS)
- The downlink (from BS to SS) (Mojtaba & Mohamed, 2013).

2.2.2 Mobility support in WiMAX

IEEE 802.16e implemented mobility support, specifying the OFDMA PHY layer and mechanisms for location and mobility management, laying the framework for mobile devices with WiMAX. The simple mobility scenario allows SSs with speeds up to 60 km/h to roam within the coverage area. The Hard Handover (HHO), Macro Handover Diversity (MDHO), and Fast Base Station Switching (FBSS) are the handover types for WiMAX network. All WiMAX mobile devices have the HHO as the only essential handover type. (IEEE Standard for Local and Metropolitan Area Networks, Part 16: Air Interface for Fixed Broadband Wireless Access Systems IEEE 802.16 – IEEE Standard 802.16, 2004).

2.3 LTE network

Long term evolution (LTE) was standardized in December 2008 in the third partnership project (3GPP) release 8. The release 8 document specifies the LTE architecture consisting of the evolved Packet Core (EPC) and the Evolved UTRAN of the LTE network. (Mohammed & Hadia, 2011).

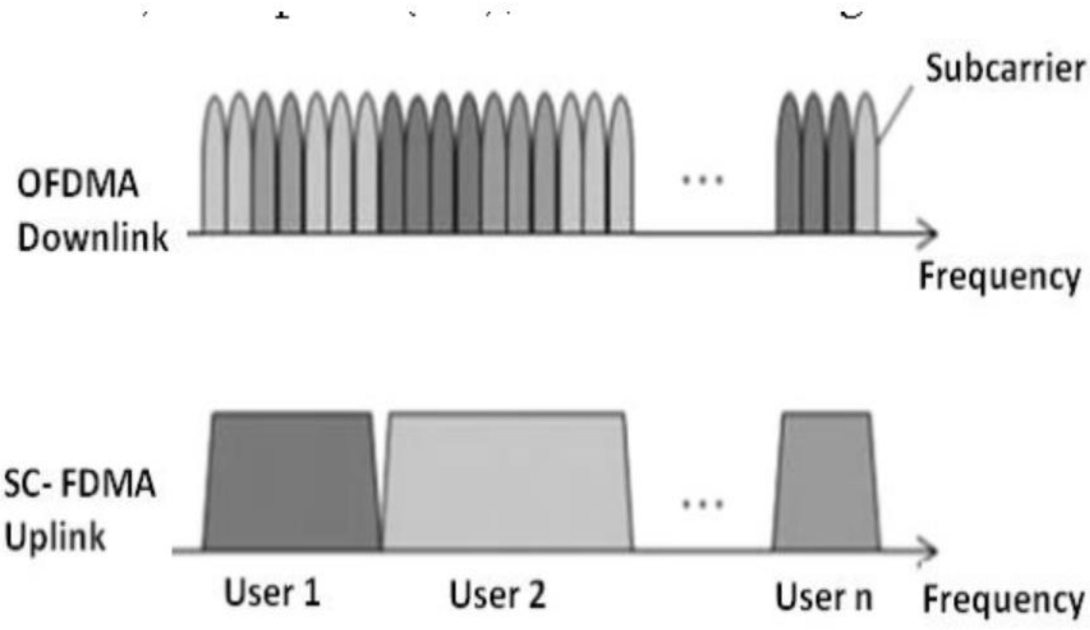


Figure 6. OFDMA downlink and SC-FDMA uplink (Nohrborg, 2019).

The 3GPP uses a multi-carrier solution to achieve higher efficiency and facilitate effective scheduling in both time and frequency domain. Thus, Orthogonal Frequency Multiple Access (OFDM) is a multi-carrier system that divides the available bandwidth into a multitude of shared narrowband orthogonal subcarriers. Within OFDM, multiple users can share these subcarriers. Orthogonal Frequency Multiple Access (OFDMA) has therefore been chosen for downlink and SC-FDMA (Single Carrier-Frequency Division Multiple Access) uplink, also known as DFT (Discrete Fourier Transform) OFDMA distributed as shown in Figure 6. (Nohrborg, 2019). The uplink Single Carrier–Frequency Division Multiple Access (SC-FDMA) and the downlink (OFDM) are the key components of LTE responsible for the transmission of data.

2.3.1 The LTE physical, logical and transport channels

The downlink and uplink data transmission have three channels, which include:

- Physical channels

The physical channels as communication channels that carry use data and control messages

- Transport channels

Transport channels are used to convey the information provided by the physical layer to the Medium Access Control (MAC) and higher layers

- Logical channels

The logical channels located within the LTE protocol system provide various services for the MAC. The downlink throughput of the LTE is greater than 100 Mbps, and that of the uplink data transmission is greater than 50 Mbps**.** LTE operates using multi-antenna techniques such as diversity, beam forming, spatial division multiple access (SDMA) and multiple inputs multiple outputs (MIMO). The OFDM performs the following functions:

- Layered bandwidth transmission
- Layered control signalling
- Structures and support to the layered environments so that the uplink and the downlink transmission can work effectively

The SC-FDMA and OFDM have similar structures, but the OFDM peak to average power ratio is low and it improves battery life. The LTE networks provide low latency, and it's cost-effective and has a higher throughput performance than the 3G network. (Nohrborg, 2019).

2.3.2 LTE architecture and deployment models

The LTE core network–the Evolved Packet Core (EPC) is the brain of the LTE network. Wireless communication with other packet data networks like the internet, the IP multimedia systems or private corporate network is established by the EPC. It consists of five nodes as shown in Figure 7:

- The mobility management entity (MME) manages the high-level operation of the signals messages to the Home Subscriber Server (HSS).

- The serving gateway (S-GW) is the router, which transmits data from the BS to the packet data network (PDN) gateway.

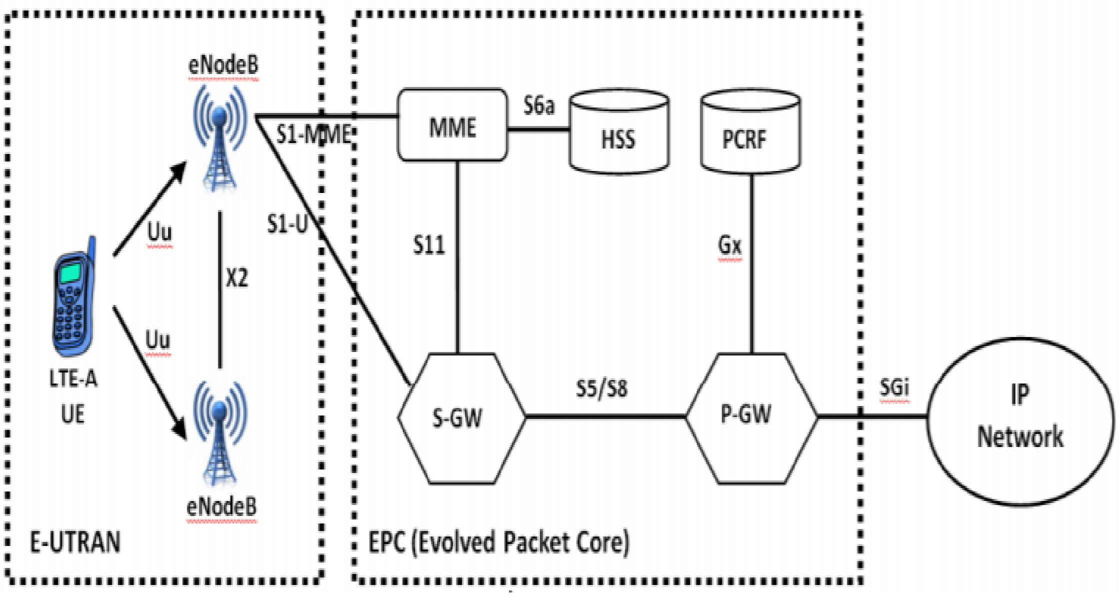


Figure 7. LTE network architecture diagram (Rakesh & Ranjan, 2016).

- The Home Subscriber Server (HSS) is a component of LTE network that acts as a central database containing information on all the subscribers of the network operator.

- P-GW: PDN connects with the rest of the world. Every packet data network is acknowledged by an access point name (APN). The role of PDN gateway is the same as that of the gateway GPRS support node (GGSN) as well as the serving GPRS support node (SGSN).

- PCRF: PCRF (Policy and Charging Rules Function) is a node responsible for real-time policy rules and charging in the EPC network. (Frederic, 2019).

3 NETWORK INTEGRATION

The European Telecommunication Standards Institute proposed the loose coupling and the tight coupling architectures for integrating different technologies of Wi-Fi, WiMAX and LTE (Khattab & Alani, 2014). Figure 10 is a loosely coupled network of Wi-Fi/LTE small cell while Figure 11 depicts a tightly coupled small cell network of Wi-Fi/LTE.

3.1 Network integration with loose coupling system

In loose coupling architecture, the respective network of Wi-Fi, WiMAX and LTE are deployed independently. There is no modification of existing architecture, and no extra cost is incurred. For a loosely coupled architecture of Wi-Fi/WiMAX, all traffic from the WLAN network is directly injected into the intermediate network. This is later transferred to the core network. (Khattab & Alani, 2014). In Figure 10, the Wi-Fi network are independently connected to the IP cloud from the Wi-Fi_Router and the LTE network through the EPC router Wi-Fi

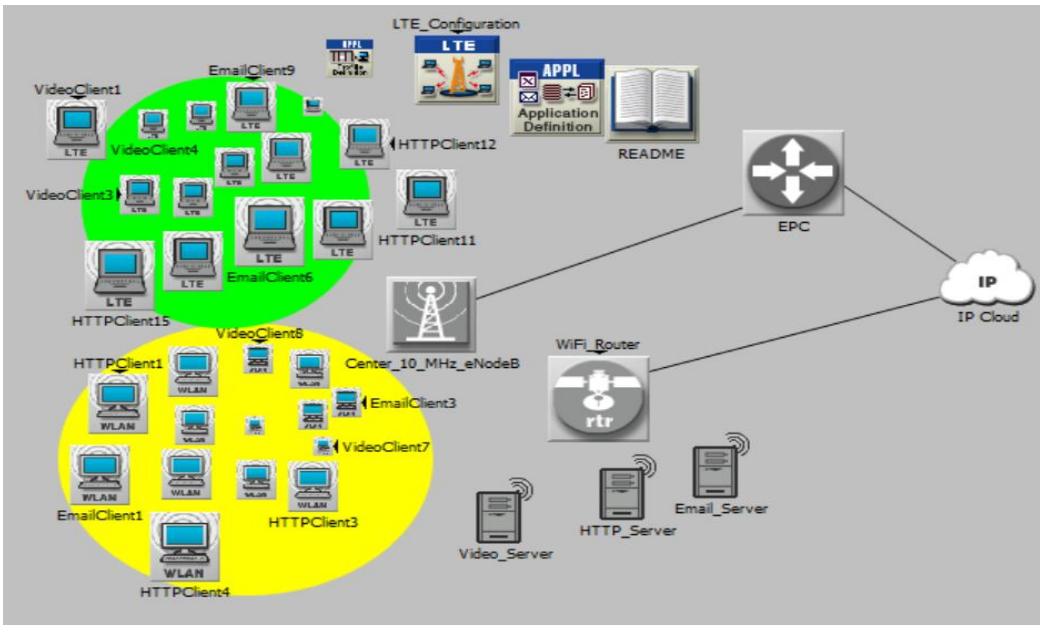


Figure 10. Diagram of the loosely coupled architecture of Wi-Fi/ LTE small cell.

3.2 Network integration with tight coupling architecture

The tight coupling system of Wi-Fi, LTE networks are not independently deployed, but rather they are initially connected through the core network before being connected to the intermediate network (Khattab & Alani, 2014). In Figure 11, the Wi-Fi network is connected to the core network of the LTE through the EPC router. And thus, the whole network is later connected to the IP cloud network.

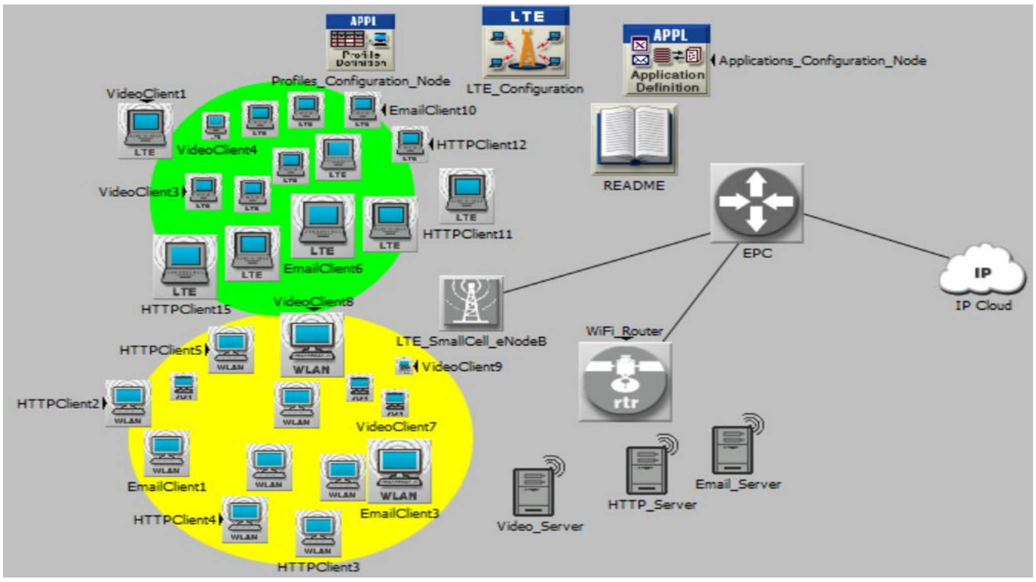


Figure 11. Tight coupled architecture

3.3 Overview of small cell

Small cell base stations are miniaturized base station of LTE or WiMAX and are of low power. They are specifically for hotspots deployments in indoor and outdoor scenarios and are considered as the panacea promising to combat mobile traffic explosion.

The pico and the femto eNB are SCBSs of low power and their transmission power (Tx) is lower than the macro BS classes. The different types of SCBSs and their coverage distances are shown in Table 4.

Small cell base stations (SCBSs) deployment is viewed as a critical solution to offload traffic, maximize coverage and boost future wireless systems capacity. The next generation of SCBSs is foreseen to be multimode capable of effectively transmitting both licensed and unlicensed bands simultaneously. This represents a cost-effective integration of both Wi-Fi and small cell that effectively copes with upsurge in wireless data traffic. Due to security issues, unlicensed nature of Wi-Fi, resource competition among many hotspots' SSs may lead to a reduced throughput. Some this traffic can be offloaded via small cell network operating over the licensed spectrum.

Small cell optimization and deployment strategy are done on both outdoor and indoor with and without macro coverage, as well as ideal and non-ideal backhaul. It is essential to consider both sparse and dense small cell deployments. (TR 36.932 version 12.1.0 Release 12, 2014).

Table 4. Small cell comparison.

Base Station Type	**Transmission Power**	**Coverage Distance(m)**	**Numbers of Subscribers**	**Locations**
Femtocell	1mW to 250mW	0.01 to 0.10	1 to 30	Indoor
Picocell	250mW to 1.0W	0.10 to 0.20	30 to 100	Indoor/Out-
Microcell	1.0W to 10.0W	0.20 to 2.00	100 to 2000	Indoor/Out-
Macrocell	10.0W to >50.0W	8.00 to 30.00	>2000	Outdoor

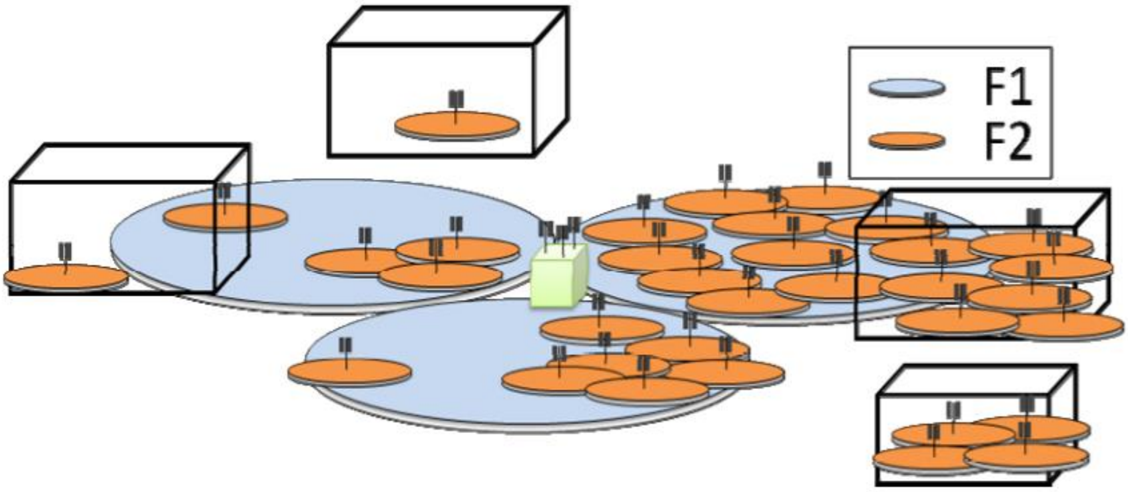


Figure 8. Small cell deployment with and without macro cell coverage (TR 36.932 version 12.1. Release 12, 2014).

3.3.1 Small cell integrated with macro base station

Small cell deployment and enhancement involve a scenario in which small cells are deployed in the coverage area overlaid E-UTRAN microcells to increase the throughput of the network already deployed. In Figure 8, F1 and F2 denote small cell and macrocell carrier frequency.

The small cell network's approach of SCBSs depends on its cell radius. The capacity of the cells is inversely related to the cell radius square. Figure 9 depicts the relationship between the cell capacity and coverage radius for different small cell types.

$$Cell\ Capacity \propto \frac{1}{cell\ radius^2} \qquad (2)$$

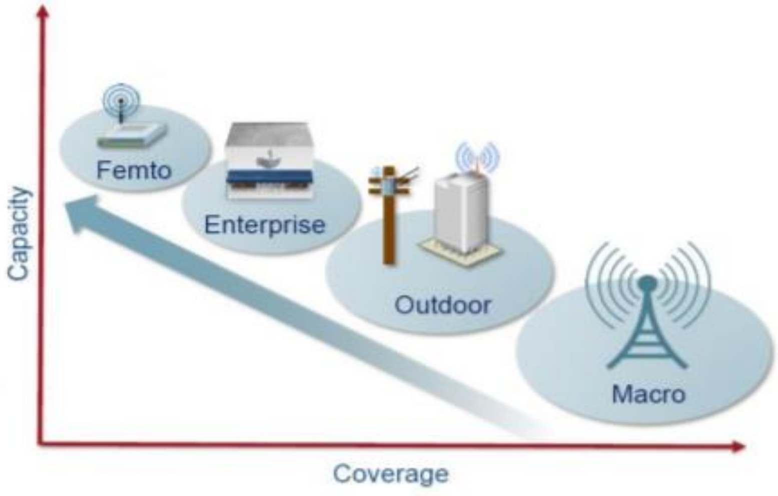


Figure 9. Graph of small cell types and capacity. (Sambanthan & Muthu, 2017).

The cell capacity is quadrupled when the cell radius is halved. As the cell radius becomes smaller, the nearer the SS to the BS. Also, SSs within the small cell coverage may have less mobility, the fading effect is less, and the network global throughput is greater than that of macrocell. (Sambanthan & Muthu, 2017).

3.4 Performance and quality of service evaluation

Five metrics are used to analyse the performance of the network. They are the global throughput, email download response time, email upload response time, HTTP page response time and the end-2-end delay (E2E delay).

3.4.1 The global throughput of a clustered network

Whenever a network is configured to run in a clustered form consisting of a fixed set of MS, the global throughput of all SSs in the clustered system is given by equation 3.

$$T(n) = \sum_{i=1}^{n} t(i) \tag{3}$$

The parameter $t(i)$ depicts the throughput of a single SS in the network and $i = 1,......., n$ According to the previous equation, as we increase the number of nodes or BS in the cluster, the value of n increases, and thus the value of $T(n)$ will change**. (**Murali, 2014).

Thus, consider a given clustered A configuration with throughput $T_1(n)$. As the number of BS or the number of SSs in the network increases, the measured throughput may increase or decrease to $T_2(n)$. T_1(n) and $T_2(n)$ are related by equation 4 and 5. For $T_2(\mathrm{n}) > T_1(\mathrm{n})$,

$$T_2(\mathrm{n}) = T_1(\mathrm{n}) + t_{increase} \tag{4}$$

where $t_{increase}$ indicates the increase in throughout. For $T_2(\mathrm{n}) < T_1(\mathrm{n})$,

$$T_1(\mathrm{n}) = T_2(\mathrm{n}) + t_{drop} \tag{5}$$

where t_{drop} denotes the drop in throughput.

3.4.2 Email download/upload response time

The email will be stored on the server when a client sends an email. The client periodically polls the server and receive emails addressed to it. In the email application model, messages are sent and received using the Transmission Control Protocol (TCP). Modern email packages use Simple Mail Transfer Protocol (SMTP) to send an email from the client to the sender and Post Office Protocol (POP) combinations. TCP is used as the underlying transport by both SMTP and POP. Thus, the email download and upload response times are the elapsed times in seconds between sending an email request and receiving an acknowledgement from the network's email server. The diagram in Figure 12 describes how the email application is modelled in Riverbed Modeler.

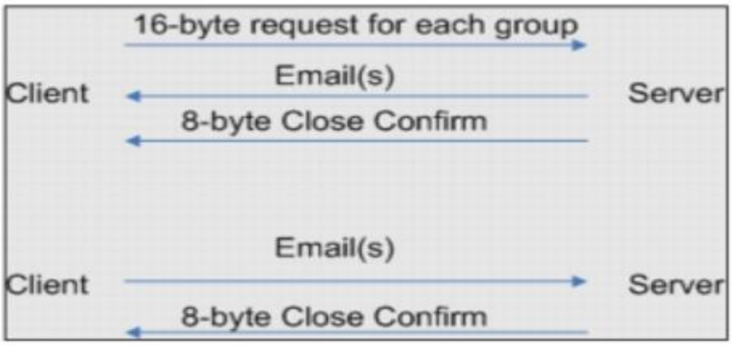


Figure 12. Email application exchange of message.

3.4.3 HTTP page response time

The hypertext transfer protocol is used in web-based applications, and it mainly involves a request and response process between a remote server and the web. When a page is downloaded from a remote server by the SS, the page contains information about text and images, and sometimes videos. These elements of the page are known collectively as "inline objects." TCP is the default HTTP communication protocol. Each request for HTTP page can result in multiple TCP connections being opened to transfer the content of the inline objects embedded in the page.

Figure 13 shows the returned requests and objects in an HTTP transaction. For every inline object, an HTTP request is sent. Therefore, the HTTP page response time specifies the time needed for all inline objects to be retrieved throughout the website. If the page contains a non-preloaded video, then this statistic does not consider the retrieval of that video.

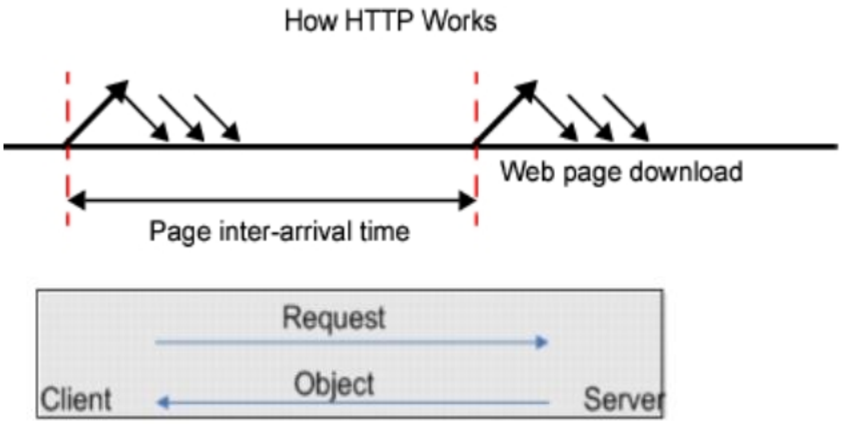


Figure 13. HTTP application message exchange.

3.4.4 Video end-to-end delay

An application for video conferencing allows SSs to transfer video frames across the network. User Datagram Protocol (UDP) is the default video conferencing communication protocol. Figure 14 shows how Riverbed Modeler models video conferencing.

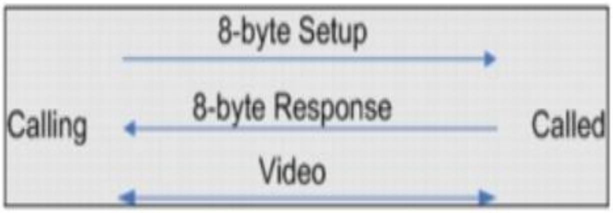


Figure 14. Exchange of message for video application.

Given two packets A and B that left the application layer at t_{a1} and t_{b1}, and arrived at the destination layer at t_{a2} and t_{b2}, the average E2E delay is given by equation 6.

$$E2E\_delay = (t_{b2} - t_{b1}) - (t_{a2} - t_{a1}) \tag{6}$$

where $E2E\_delay$ is the E2E delay. (Zhu & Li, 2013).

The E2E delay is, therefore, the time taken in seconds to send a video application packet from the source node to the destination node. (Riverbed online documentation).

3.5 Overview of TCP congestion control algorithm

This section describes the four algorithms for congestion control: slow start, congestion avoidance, fast retransmit and fast recovery. TCP congestion control uses packet loss as the congestion signal. An acknowledgement (ACK) is forwarded back to the sender whenever it sends a packet over the network. The sender (or source) controls the packet sending rate using a congestion window (cwnd) variable which specifies the number of packets allowed to be sent by the source. The receiver also advertises the amount of data it can buffer for the link called the congestion window for the receiver (rwnd).

A TCP sender can only send data if the number of packets to be send is less that the limit permitted by the algorithms. Data cannot be sent when the cwnd value is greater than the congestion threshold.

A packet loss signifies that the link has reached the end of the congestion stage, the algorithm moves consequently moves again to the start of the congestion stage, as shown in Figure 15. The vertical part of the graph denotes packet loss while the linearly increasing line indicates the congestion avoidance phase. (Mudassar, et al., 2015)**.**

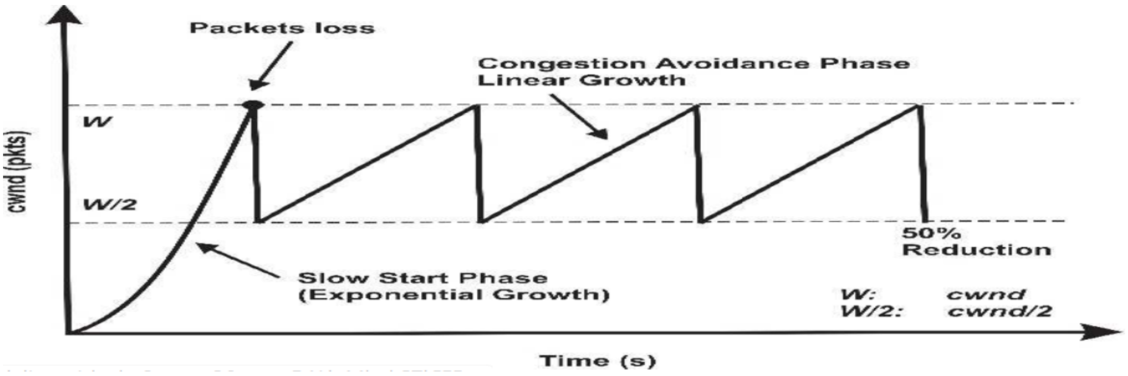


Figure 15. TCP congestion control mechanism. (Mudassar, et al., 2015)**.**

The Bandwidth Delay Product (BDP) in bits is equal to the available capacity of the wireless connection and its E2E delay. The E2E delay can be calculated using Round-Trip Time (RTT), and B (bandwidth), as depicted in Equation 7.

$$BDP(bits) = B\ x\ RTT \tag{7}$$

To avoid packet loss, the amounts of packets in-flight or unacknowledged, must not exceed the share of BDP value of the TCP window size. (Haniza, et al., 2009).

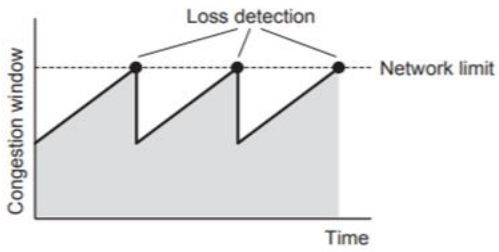


Figure 16. Packet loss as spikes in congestion window. (Afanasyev, et al., 2015).

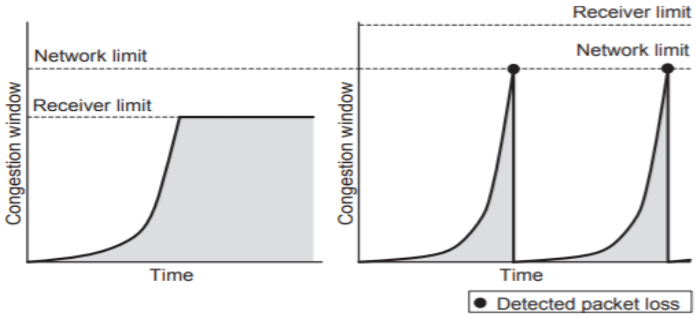


Figure 17. Diagram showing receiver and network limit. (Afanasyev, et al., 2015).

3.5.1 TCP slow start and congestion avoidance

The slow start algorithm estimates the capacity of the network (or the network unknown equilibrium condition) by increasing the congestion window exponentially. The level of slow start (ssthresh) can be arbitrarily high and should be lowered when congestion occurs and is an approximate conservative measure of the network path bandwidth of the available link. Equation 10 shows the general TCP while equations 8 and 9 depicts the cwnd during congestion avoidance when the ACK is received and when the loss is observed. (Mudassar, et al., 2015).

$$ACK\colon cwnd \leftarrow cwnd + \frac{1}{cwnd}\ if\ (cwnd \geq ssthresh) \tag{8}$$

$$Loss\colon cwnd \leftarrow \frac{1}{2cwnd} \tag{9}$$

$$AIMD\colon \begin{Bmatrix} ACK\colon cwnd \leftarrow cwnd + \dfrac{\alpha}{cwnd} \\ loss = cwnd \leftarrow (1-\beta)cwnd \end{Bmatrix} \tag{10}$$

At this point, there will be no packet loss because the slow start algorithm is applied to increase transmission rate significantly to fill the bandwidth available. After the ssthresh have reached transmission rate**,** if cwnd > ssthresh, congestion avoidance is used to monitor the capacity of the network more slowly than at slow start stage.

Cwnd window rapid growth continues until the packet loss has been detected as shown in Figure 16, enabling the slow-start threshold value (ssthresh) to be changed to ssthresh = cwnd/2. The connection begins again by setting cwnd =1 after losing the packet and increases exponentially until the cwnd = ssthresh. (Ghassan, et al., 2012).

3.5.2 Fast transmission and recovery mechanism

If three duplicate ACKs are detected, TCP shifts from congestion avoidance to fast retransmission. The receiver finds the incoming packets as out of order when there is a packet loss. The fast recovery algorithm stops when the ACK of lost data is received by the source. The model again moves from fast recovery to fast retransmit any time a packet is received and may change back to start transmission if a packet loss occurs**.** (Mudassar, et al., 2015).

4 DESIGN AND IMPLEMENTATION

The loose coupling system was designed for Wi-Fi/LTE and Wi-Fi/WiMAX architectures. The first task was to design a system with a macro BS located at a certain distance from the network. The number of SSs in these designs was thereafter increased.

SCBSs were deployed and integrated with the network. Their roles were analyzed in optimizing the performance of these systems whose global throughput and user experience have decreased due to the increase in the network traffic or the effect of the location of the macro BS from the network.

In the later part of the design, a loose coupling architecture of Wi-Fi/WiMAX and Wi-Fi/LTE were designed and compared. WiMAX and LTE macro BS were configured with parameters to model an SCBS. These designs were completely independent of the existing E-UTRAN macro cell coverage.

The simulation comprises of SSs, BSs (small and macro cells), routers or access point, an application, and a profile definition object. The various traffics used in the simulation was define by the application and profile definition. A mixture of video streaming, HTTP, and email application was used in this simulation. The respective parts of the simulation are outlined in sections 4.2 to 4.6.

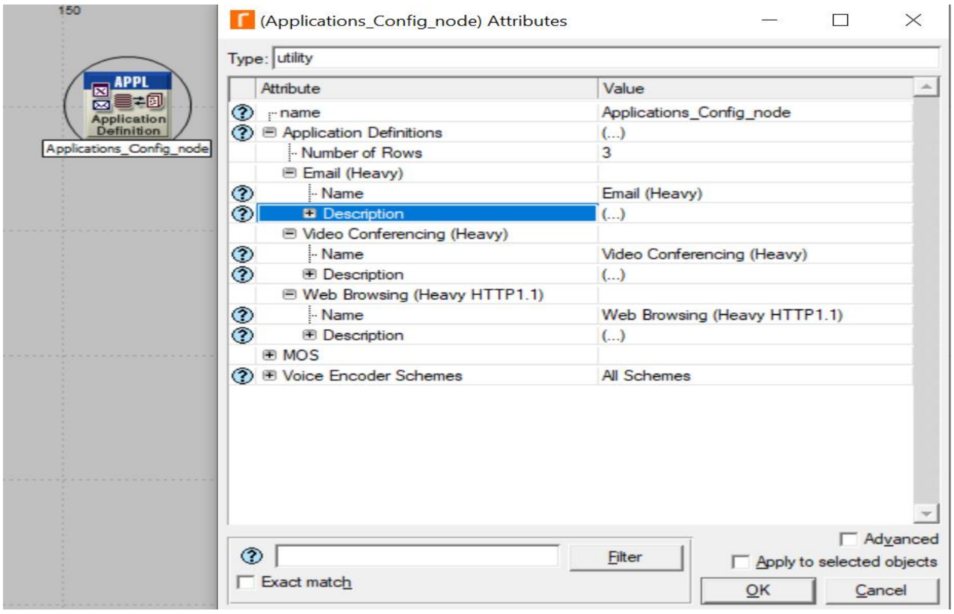
4.1 Overview of riverbed modeler

Performance evaluation of a well-designed network model and the model itself is critical in real-world scenarios. Nonetheless, in a real scenario, the method of performance evaluation is a complex and challenging task. Popular open-source simulators like NS-2 and NS-3 are too complicated to use in real-world scenarios. (Masum & Babu, 2011).

Riverbed Modeler, on the other hand, is a commercial simulator where the source code of the kernel is not available. Nevertheless, it has built-in rich and detailed development features that make it easier to design the real-world scenario and simulate network models. This offers extensive options as both an object-oriented and a network simulator based on the Discrete Event System (DES). Riverbed software models the process actions effectively by each event in the system by DES. It allows modelers to include models with a wide range of generic and vendor-specific communication network. It includes a diverse development environment with a range of features that support both distributed systems and network modelling. The graphical interface enables displaying the results. The results of Riverbed are robust. (Riverbed Online Documentation).

4.2 Application configuration for email, video, and HTTP

Three rows of applications were defined for video, email and HTTP application names, and their corresponding description is selected from available application types, as shown in Figure 18.



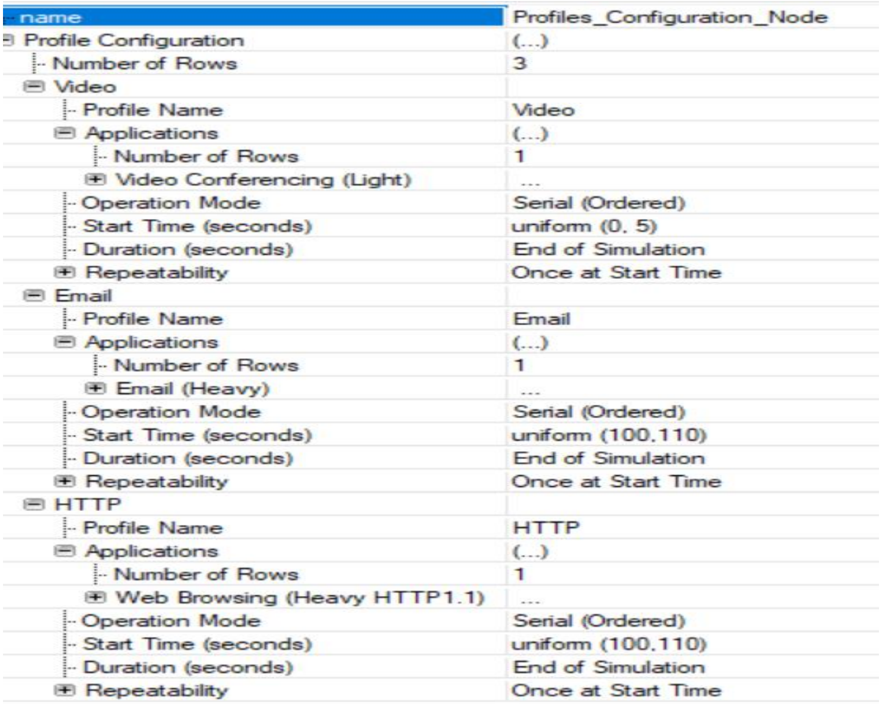
Type: utility

Attribute	Value
name	Applications_Config_node
⊟ Application Definitions	(...)
Number of Rows	3
⊟ Email (Heavy)	
Name	Email (Heavy)
⊞ Description	(...)
⊟ Video Conferencing (Heavy)	
Name	Video Conferencing (Heavy)
⊞ Description	(...)
⊟ Web Browsing (Heavy HTTP1.1)	
Name	Web Browsing (Heavy HTTP1.1)
⊞ Description	(...)
⊞ MOS	
⊞ Voice Encoder Schemes	All Schemes

Figure 18. Application configuration.

4.3 Profile configuration different traffic types

The "Profile Config" node uses the three rows of applications–email, video and HTTP defined in the application config. Three different types of traffics were created by setting the numbers of rows to 3 in the profile config and creating a profile name for each application. In the video application profile, a video conferencing (Heavy) was selected. In email profile, an email (Heavy) and lastly in HTTP profile, a web browsing (Heavy HTTP1.1) was selected. The diagram in Figure 19 shows the various specifications. Thus, this application was specified on all SSs in the network to generate application layer traffic.



name	Profiles_Configuration_Node
⊟ Profile Configuration	(...)
Number of Rows	3
⊟ Video	
Profile Name	Video
⊟ Applications	(...)
Number of Rows	1
⊞ Video Conferencing (Light)	...
Operation Mode	Serial (Ordered)
Start Time (seconds)	uniform (0, 5)
Duration (seconds)	End of Simulation
⊞ Repeatability	Once at Start Time
⊟ Email	
Profile Name	Email
⊟ Applications	(...)
Number of Rows	1
⊞ Email (Heavy)	...
Operation Mode	Serial (Ordered)
Start Time (seconds)	uniform (100,110)
Duration (seconds)	End of Simulation
⊞ Repeatability	Once at Start Time
⊟ HTTP	
Profile Name	HTTP
⊟ Applications	(...)
Number of Rows	1
⊞ Web Browsing (Heavy HTTP1.1)	...
Operation Mode	Serial (Ordered)
Start Time (seconds)	uniform (100,110)
Duration (seconds)	End of Simulation
⊞ Repeatability	Once at Start Time

Figure 19. Video, email and HTTP pattern specification in profile config node.

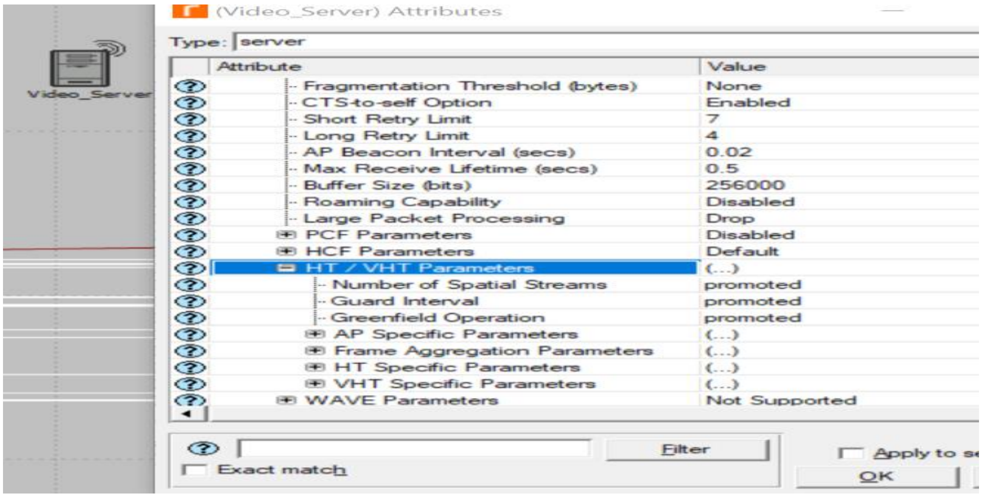
4.4 WLAN nodes, router and servers configuration

The WLAN parameters in Table 5 were configured on all Wi-Fi nodes: Wi-Fi_router, Email_Server, HTTP_Server, Video_Server, and WLAN clients.

Table 5. WLAN parameter configuration.

WLAN Parameter	**Configuration**
Physical Characteristics	VHT PHY (802.11ac)
Data Rates (bps)	78 Mbps (base) / 3.18 Gbps (Max)
BSSID	0

The Wi-Fi HT/VHT parameter for all SSs and all servers in the network was configured with the attribute ‘promoted’ as seen in the diagram in Figure 20.

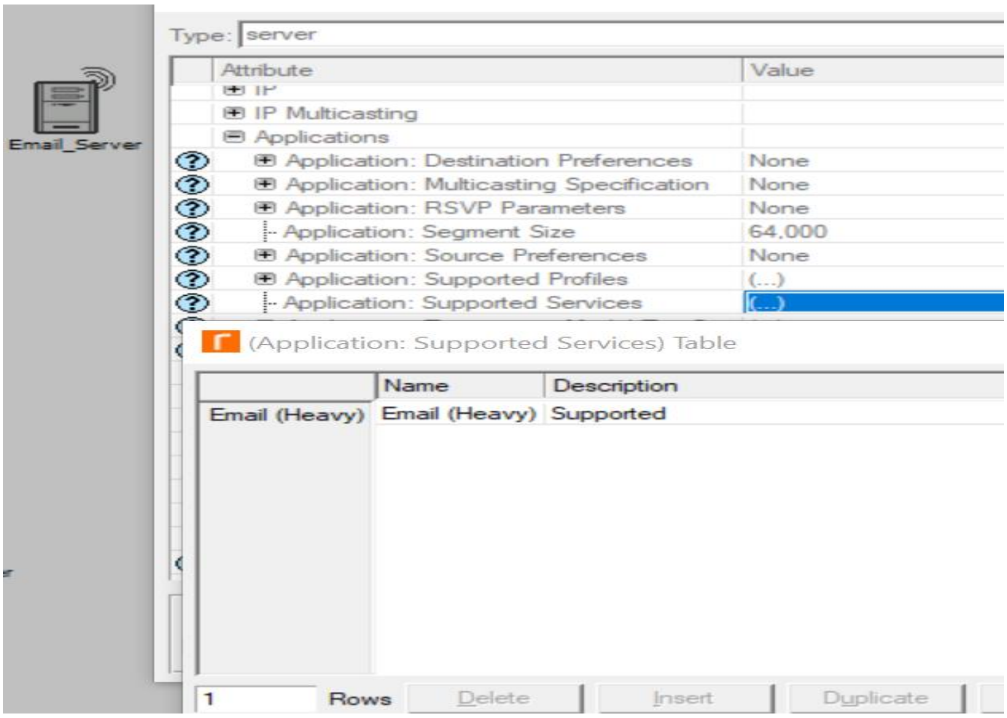


Type: server

Attribute	Value
Fragmentation Threshold (bytes)	None
CTS-to-self Option	Enabled
Short Retry Limit	7
Long Retry Limit	4
AP Beacon Interval (secs)	0.02
Max Receive Lifetime (secs)	0.5
Buffer Size (bits)	256000
Roaming Capability	Disabled
Large Packet Processing	Drop
PCF Parameters	Disabled
HCF Parameters	Default
HT / VHT Parameters	(...)
Number of Spatial Streams	promoted
Guard Interval	promoted
Greenfield Operation	promoted
AP Specific Parameters	(...)
Frame Aggregation Parameters	(...)
HT Specific Parameters	(...)
VHT Specific Parameters	(...)
WAVE Parameters	Not Supported

Figure 20. Wi-Fi HT/VHT parameter configuration.

Three servers are selected and configured with email, video and HTTP application packets. The server configuration for email is shown in Figure 21.



Type: server

Attribute	Value
IP	
IP Multicasting	
Applications	
Application: Destination Preferences	None
Application: Multicasting Specification	None
Application: RSVP Parameters	None
Application: Segment Size	64,000
Application: Source Preferences	None
Application: Supported Profiles	(...)
Application: Supported Services	(...)

(Application: Supported Services) Table

	Name	Description
Email (Heavy)	Email (Heavy)	Supported

1 Rows

Figure 21. Email server configuration.

4.5 WIMAX design parameters

In this section, WiMAC MAC service class and the WiMAX OFDMA are configured with appropriate parameters.

4.5.1 WIMAX MAC service class definition

The WiMAX Service Class parameters in the WiMAX configuration node (WiMAX_config_node) are configured as seen in Table 6.

Table 6. WiMAX service class parameters

WiMAX service class parameters	**Configuration**
Service class name	Silver
Scheduling type	rtPS
Maximum Sustained Traffic Rate	32 kbps
Minimum Reserved Traffic Rate	32 kbps
Maximum Latency	30.0
Maximum Traffic burst	0

4.5.2 Configuration of WiMAX OFDMA

OFDMA specifications in Table 7 were defined in accordance with the provisions of WiMAX 802.16 using the WiMAX configuration node.

Table 7. OFDMA parameter configuration

OFDMA Parameters	**Configurations**
Bandwidth	20 MHz
Base Frequency	2.5 GHz
Symbol Duration	100.8
Numbers of Subcarriers	2048
Duplexing Technique (TDD)	TDD.

4.6 LTE parameters

LTE parameters used in this simulation comprises of LTE nodes descriptions and configuration for LTE small cell base station for an in-door scenario.

Table 8. LTE small cell configurations.

LTE TDD Channel parameters	**Configurations**
Antenna gain (dBi)	5.0
Maximum Transmission Power	0.5
Base frequency	2.6 GHz
Numbers of Transmit Antennas	2
Numbers of Received Antennas	2

Table 9. LTE nodes and application descriptions.

Node Model/Applications	**Description**
lte_wkstn_adv	The node model represents LTE workstation
ethernet4_slip8_gtwy	This node model is an IP-based gateway that supports four Ethernet hub devices and eight serial line interfaces. .
lte_enodeb_4ethernet_4atm_4slip_adv	This device is an LTE enodeB
LTE configuration node	This device is used to store PHY parameters and EPS Bearer descriptions, which all LTE nodes on the network will access. The LTE configuration node is described in Figure 24 as LTE Configuration

4.7 Throughput improvement with small cell base station

This section consists of two scenarios. Scenario 1 involves a WiMAX macro BS placed at strategic distances from the network such that a point where there exists a significant decrease in throughput can be located. The WiMAX macro BS is designed according to the parameters in Table 10.

In scenario 2, the traffic load of the network is randomly increased to observe a throughput drop. In both scenarios, the network was integrated with SCBS whenever there exists a loss in throughput.

Table 10. WiMAX macro cell parameters.

WiMAX macro cell parameters	**Configuration**
Antenna gain (dBi)	15.0
Maximum transmitted power (W)	15.0
Base frequency	2.5 GHz
Propagation model	In-door

Table 11. WiMAX small cell parameters.

WiMAX macro cell parameters	**Configuration**
Antenna gain (dBi)	15.0
Maximum transmitted power (W)	15.0
Base Frequency	2.5 GHz
Propagation model	In-door

4.7.1 Scenario 1: Macro base station located farther away from the network

Scenario 1 consist of four test cases. The first, second and third test cases involve a Wi-Fi/WiMAX architecture with macro BS placed at distances 1520 m, 1525 m and 1530 m from the network. These distances are randomly chosen in order to locate a point where the WiMAX throughput gradually starts to decrease.

The Wi-Fi and WiMAX networks are integrated by two wireless routers named Wi-Fi_WiMAX_router_0 and Wi-Fi_WiMAX_router_1 as shown in Figure 22. The servers, routers, IP cloud, profile and application configuration nodes are configured according to the description in subsections 4.2 to 4.6. Each of the Wi-Fi and the WiMAX network consists of 5 video SSs, 5 HTTP SSs and 5 email SSs. Thus, the total number of SSs on both networks is 30.

The first, second and third test cases involve a Wi-Fi/WiMAX architecture with macro BS placed at distances 1520 m, 1525 m and 1530 m from the network, respectively. These distances are randomly chosen to locate a point where the WiMAX throughput gradually starts to decrease.

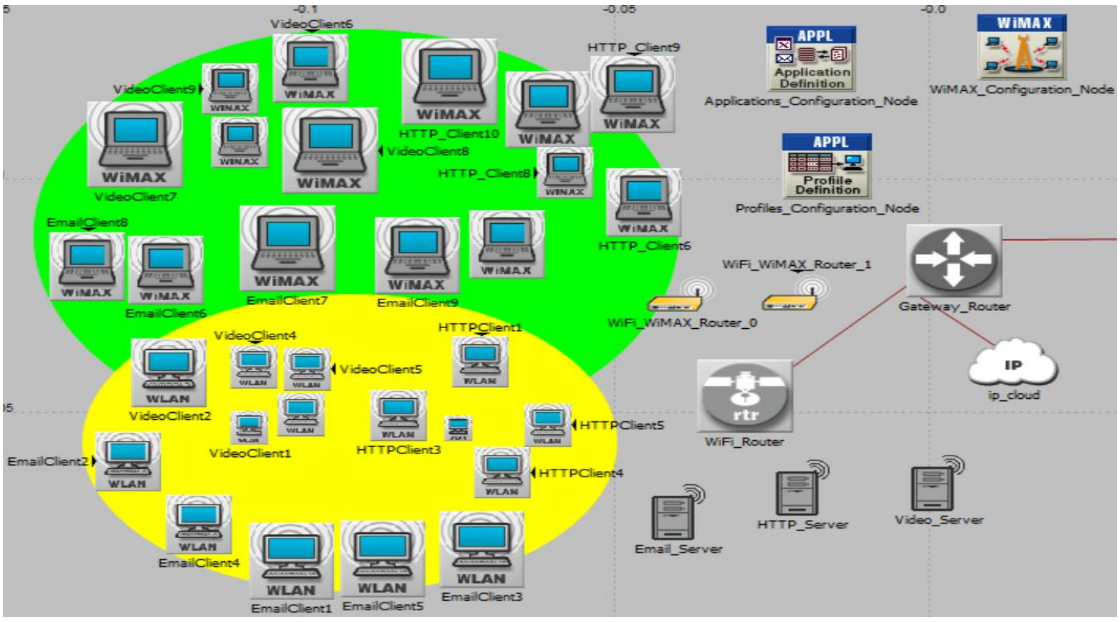


Figure 22. Wi-Fi/WiMAX network without small cell BS.

In test case 4, a single SCBS is integrated with the WiMAX macro BS when the global throughput decreases. The parameters of configuration of the SCBS and macro BS are shown in Tables 10 and 11. Thus, the diagram in Figure 22 shows a WiMAX network without SCBS. The respective positions of the BS are shown in Figure 23, which is a continuation of Figure 22.

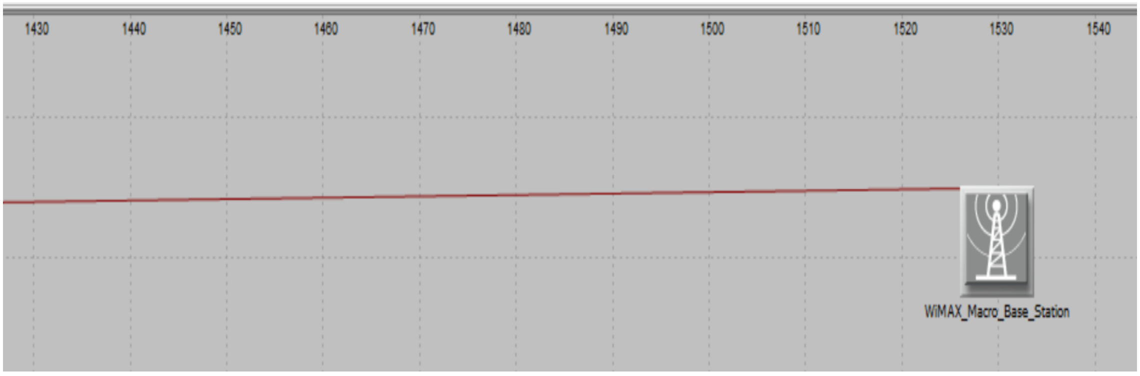


Figure 23. WiMAX macro BS at 1530 m from the network.

The macro BS from Figure 23 is at 1530 m. It is carefully moved from distances 1520 m to 1525 m until finally at 1530 m where a significant loss in throughput was observed.

Table 9. Scenario 1: Macro base station located farther away from the network.

Parameters	**SCENARIO 1**			
	Test Case 1	**Test Case 2**	**Test Case 3**	**Test Case 4**
Base Station type	WiMAX Macro BS at 1520 m	WiMAX Macro BS at 1525 m	WiMAX Macro BS at 1530 m	WiMAX Micro BS integrated with SC
Architecture type	Loose Coupling	Loose Coupling	Loose Coupling	Loose Coupling

4.7.2 Scenario 2: Large increase in network load

This scenario consists of four test cases, as shown in Table 12. In test case 1, a Wi-Fi/WiMAX loose architecture consisting of a total of 30 each of WiMAX and Wi-Fi SSs is designed. Thus, there are 15 Wi-Fi clients and 15 WiMAX SSs. In each network, there are 5 HTTP SSs, 5 video conferencing SSs and 5 email SSs running concurrently.

In test case 2, the network load of this architecture is randomly increased to 60 Wi-Fi clients and 53 WiMAX SSs to model real-life traffic increase. The Wi-Fi network consists of 20 video conferencing, 20 HTTP and 20 email applications, and the WiMAX network consists of HTTP, video and email applications randomly distributed in the network. Thus, in test case 3, a single SCBS is introduced, and in the last test case, the number of SCBSs is increased to two.

Table 12. Scenario 2: Large increase in network load.

Parameters	**SCENARIO 2**			
	Test case1	**Test case 2**	**Test case 3**	**Test case 4**
Base station type	WiMAX Macro BS	WiMAX Macro BS	Macro integrated with one SC	WiMAX macro BS integrated with two SCBSs
Number of SS	30	113	113	113

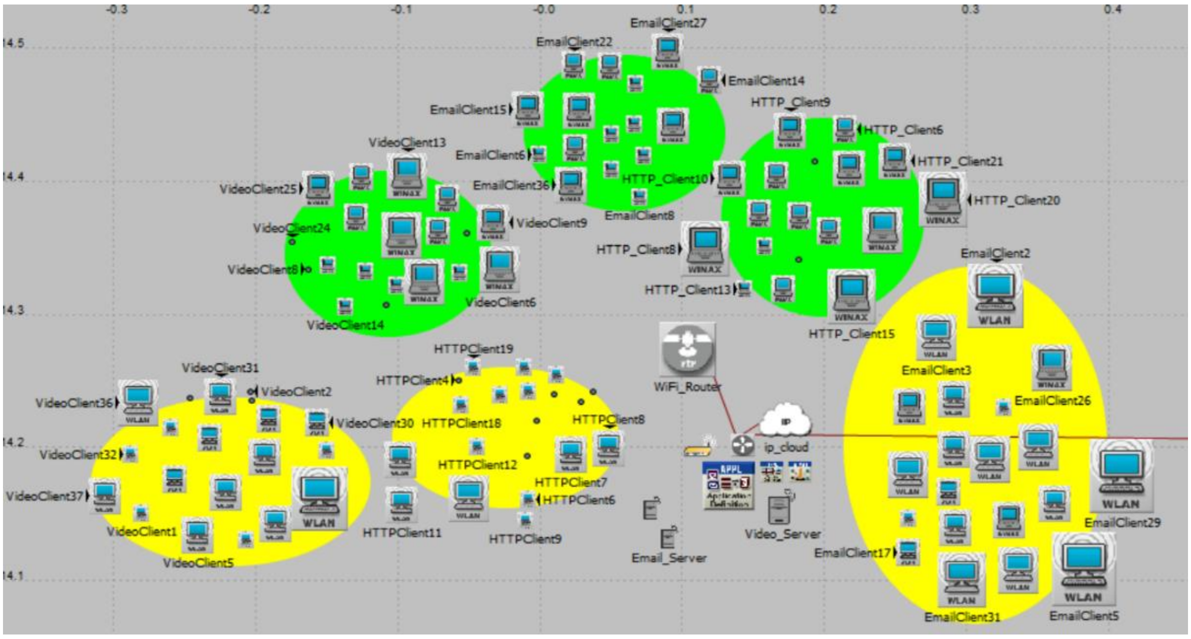


Figure 24. Small cell network consisting of 53 WiMAX and 60 Wi-Fi clients.

4.8 Scenario 3: Independently deployed small cell and Wi-Fi integration

This scenario aims to evaluate the performance of Wi-Fi/WiMAX and Wi-Fi/LTE architecture with small cells independently deployed–that is the SC has no corporation with existing macro BS.

Thus, the first and second test cases consist of loosely coupled Wi-Fi/WiMAX and Wi-Fi/LTE network. Both networks consist of 30 SSs running email, HTTP and video conferencing applications simultaneously. The WiMAX base station and the LTE eNodeB are configured with parameters to model an SCBS, as shown in Table 10 and 8**.** This type of network is specifically relevant for the large establishment and in-door scenarios seeking coverage expansion beyond the Wi-Fi network. The last scenario consists of a Wi-Fi network of 30 SSs. Table 13 depicts a summary of all test cases and Figure 25 illustrates test case 1.

Table 13 Scenario 3: Independently deployed small cells and Wi-Fi network.

Parameter	**SCENARIO 3**		
	Test Case 1	**Test case 2**	**Test case 3**
Base Station	WiMAX SC BS	LTE BS	Wi-Fi
Subscriber Station	30	30	30
Architecture Type	Loose	Loose	Not applicable

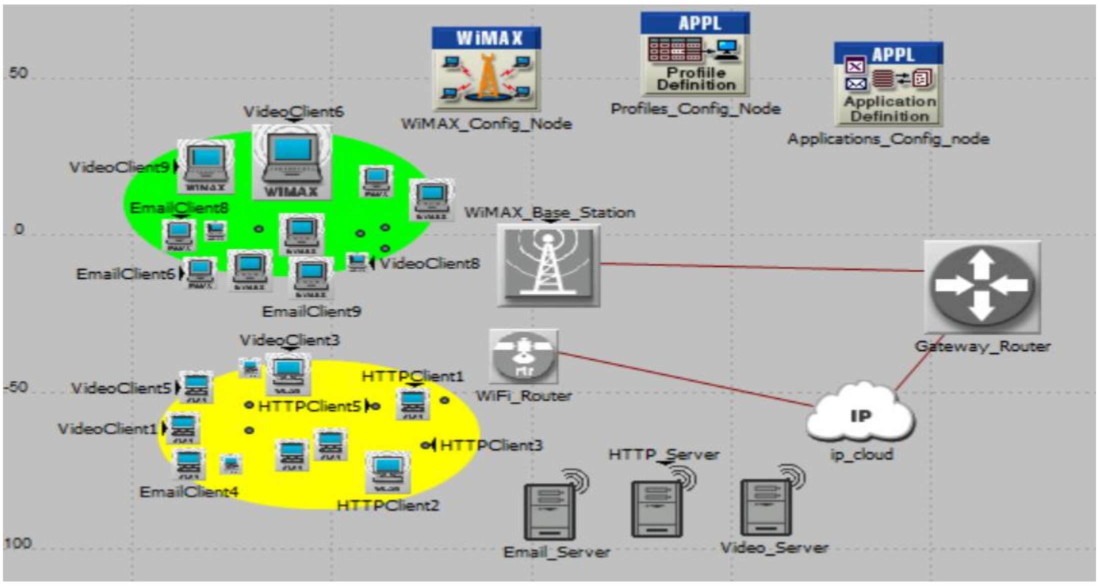


Figure 25. Independently deployed Wi-Fi/WiMAX loosely coupled architecture.

4.9 Scenario 4: LTE downlink throughput of typical applications

In this scenario, LTE/Wi-Fi small cell is tested on different applications to investigate which applications the LTE downlink throughput of the network is enhanced. In case 1, the Wi-Fi/LTE small cell is tested on video application. The network consists of 30 SSs all running video application.

In test case 2, HTTP, email and video conferencing applications are configured on the Wi-Fi/LTE network. Thus, the system consists each of 5 email SSs, 5 HTTP SSs and 5 video conferencing SSs on the Wi-Fi and WiMAX networks, respectively.

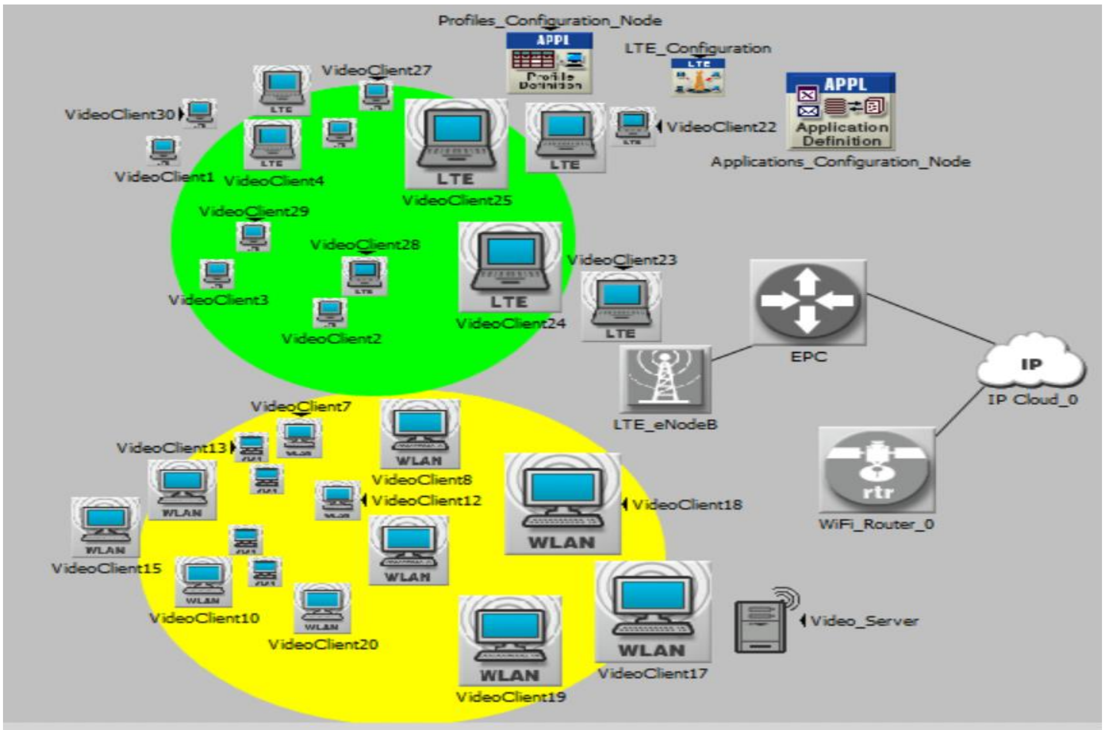


Figure 26. A network consisting of 30 video subscriber stations.

Test cases 3 and 4 are like similar to test cases 1 and 2 except that the network is configured separately with email and HTTP applications. Thus, test case 3 consist of 30 email clients and case 4 is composed of 30 SSs running HTTP applications**.** A summary of scenario 4 is given in Table 14.

Table 14 Scenario 4: Wi-Fi/ LTE small cell applications test.

Parameters	**SCENARIO 4**			
	Test Case 1	**Test Case 2**	**Test Case 3**	**Test Case 4**
Number of Subscriber Station	30	30	30	30
Application type	Video	Email, HTTP and Video	Email	Email, HTTP and Video

5 RESULTS AND ANALYSIS

5.1 Throughput analysis

In scenario 1, a drop in throughput as the network is positioned far away from the macro BS was observed. In scenario 2, analysis is done for a throughput drop as the traffic load of the network increases. Thus, in both cases, small cell was used to optimise the throughput of the network.

The values in Table 15, 16, 17 and 18 were done by exporting the respective graph to MS word and calculating their average values. All calculations in the aforementioned tables are approximately the same values when reading directly from their graphs**.**

5.1.1 Scenario 1: Throughput analysis for macro base station located farther from the network

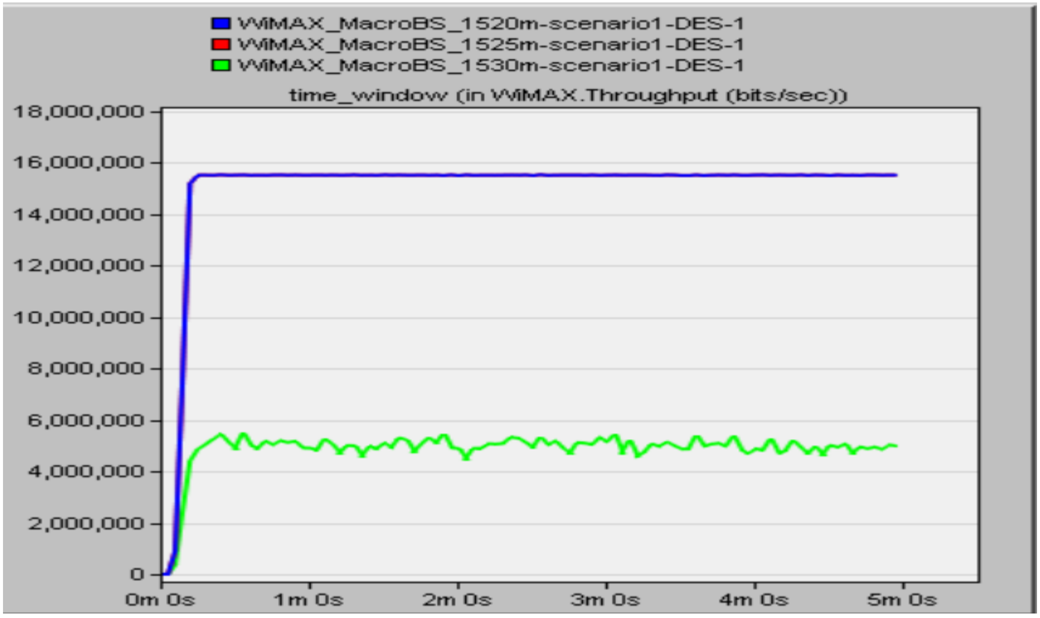


Figure 27. WiMAX macro BS at various distances for test cases 1, 2 and 3.

In Figure 27, the topmost portion of the graph, denotes a Wi-Fi/WiMAX network with macro BS strategically located at a distance 1520 m from the network (test case 1). The red line denotes case 2. Test cases 1 and 2 intercept each other. According to the analysis of the average values of the graph of Figure 27, as shown in Table 15, the network experienced a slight throughput drop in test cases 1 and 2 from a value of 15.12 Mbps to 14.27 Mbps as the BS is moved from 1520 m to 1525 m. Thus, the loss in throughput amounts to 0.85 Mbps.

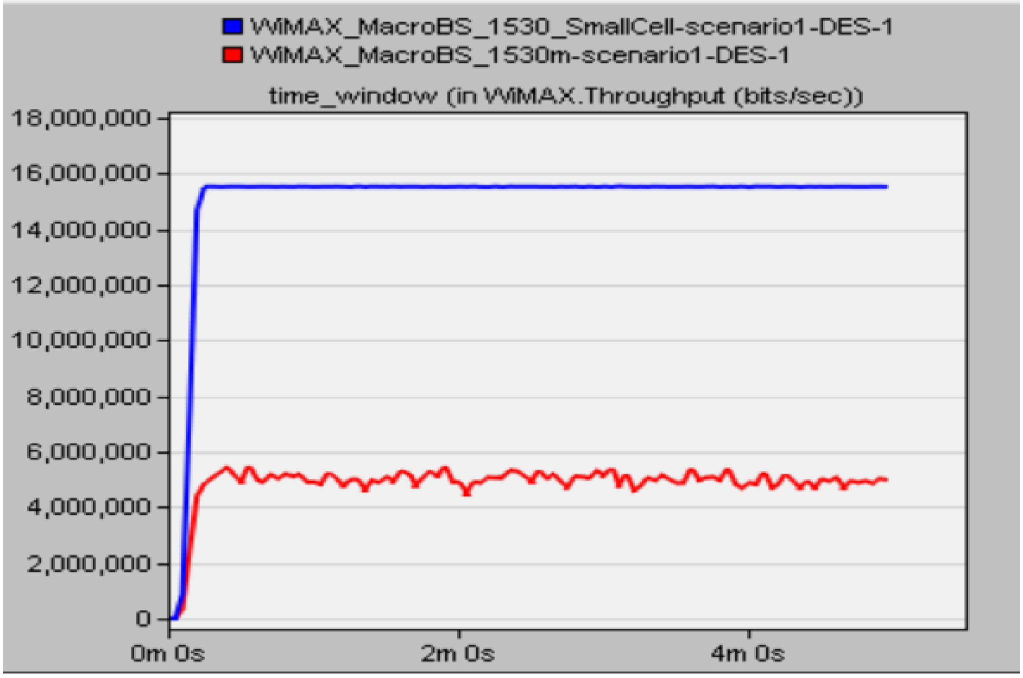


Figure 28. WiMAX macro BS integrated with small cell for test cases 3 and 4.

In test case 3, a remarkable drop in throughput occurs, from 15.12 Mbps to 4.80 Mbps, as the macro BS is moved another 5 m (from 1525 m to 1530 m). The throughput loss is approximately 10.32 Mbps. The blue line in Figure 28 depicts the integration of a small cell base station into the network. The red line represents a network without a small cell.

Table 15. Maximum and average throughput of scenario 1.

Scenario 1	**Max throughput (Mbps)**	**Average throughput (Mbps)**	**Throughput drop (Mbps)**
Case 1	15.53	15.12	0
Case 2	15.53	14.27	0.85
Case 3	5.00	4.80	10.32
Case 4	15.54	15.28	0.16

From equation 5 on page 32 above, $T_1 = 15.12\ Mbps$ is the global throughput. That is the overall throughput of the network when no parameter of investigation is at yet changed–in this case, the position of the macro BS from the network.

For case 1, $t_{drop} = 0$ since $T_1 = T_2$

For case 2, $t_{drop} = 15.12 - 14.27 = 0.85\ Mbps$ where $T_2 = 14.27\ Mbps$

For case 3, $t_{drop} = 15.12 - 4.80 = 10.32\ Mbps\ T_2 = 4.80\ Mbps.$

From equation 5 on page 32 above,

For case 4, $t_{increase} = 15.28 - 15.12 = 0.16\ Mbps$

Or $t_{drops} = -0.16\ Mbps\ \ t_{increase} = -t_{drop}$

Since t_{drop} for case 3 $>$ t_{drop} for case 2 $>$ t_{drop} for case 1, it is easy to observe that the further the macro BS is from the network, the higher the throughput drop t_{drop}.

From case 3 to 4, the t_{drop} diminishes and attain a negative value, as the throughput of the network with SCBS becomes higher than the network without SCBS.

Furthermore, the average throughput of the network in test cases 3 and 4 rose from 4.80 $Mbps$ to 15.28 $Mbps$–approximately a 218.33% rise in throughput by the introduction of a single SCBS.

5.1.2 Scenario 2: Large increase in network load

The red line (test case 1) in Figure 29 is a Wi-Fi/WiMAX network of 30 clients. The blue graph depicts a network of 113 clients (test case 2). Thus, as the number of SSs in the network increases randomly from 30 to 113, a corresponding throughput drop from 15.12 $Mbps$ to 4.68 $Mbps$ is observed.

The graph of test case 2 is not entirely a straight line as a small spike is observed at about 4 min of simulation time. As the network load increased to 113 clients, the packets sent to the receiver also correspondingly increase. Thus, the linear part of the blue line at the 4 min of simulation time, is a spike in network load (that is packets in the network that need to be sent to the receiver). Since all packets cannot be sent at once (due to the increase in network load and limited bandwidth), a spike is then formed. The linear increase in traffic load is similar to the TCP congestion control mechanism described on page 36 and in Figure 17. The linearly decreasing part of the spike indicates packet loss, as this is implemented as congestion reaches the network threshold limit of 6Mbps.

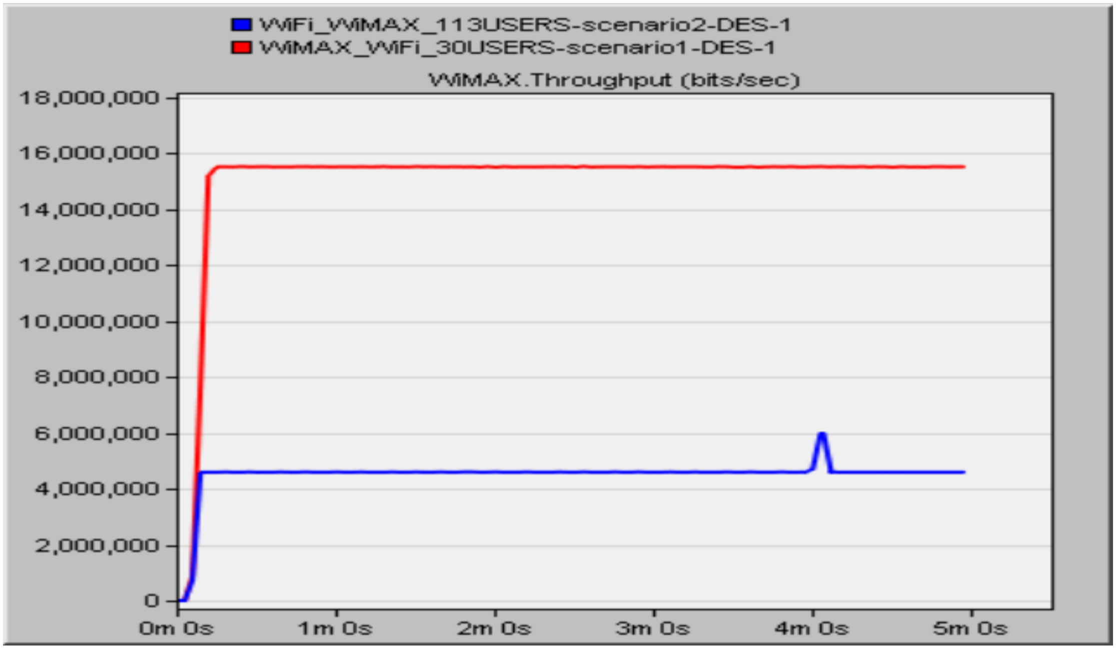


Figure 29. Graph of throughput drop with increase in traffic load.

Figure 30 represents test cases 1, 2 and 3. The blue line depicts the test case 2–the Wi-Fi/WiMAX network of 113 SSs. Thus, this is a network with no small cell BS. The red line shows a network with a single small cell (test case 1). As clearly seen from the results of test cases 1 and 2, the global throughput has decreased significantly, and to optimise it, an SCBS is introduced as illustrated by the light green straight-line in Figure 28.

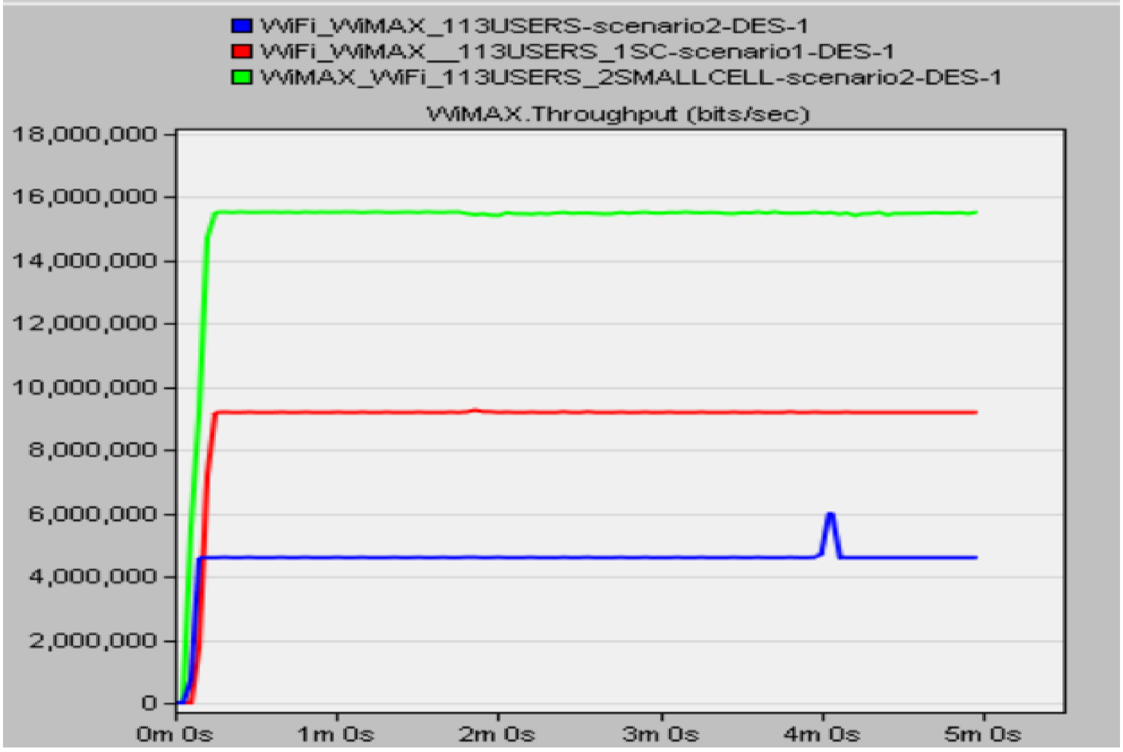


Figure 30. Throughput improvement with small cell.

Using equation 5 on page 32 above, $T_1 = 15.12\ Mbps$ denotes the throughput of the network without SCBS. For case 1, $t_{drop} = 0$ since $T_1 = T_2$

For case 2, $t_{drop} = 15.12 - 4.68 = 10.44\ Mbps$ where $T_2 = 4.68\ Mbps$

For case 3, $t_{drop} = 15.12 - 8.65 = 6.47\ Mbps$ for $T_2 = 8.65\ Mbps$

In test case 4, the throughput of the network with two SCBSs is now greater than the network without SCBS.

For test case 4, $t_{increase} = 15.33 - 15.12 = 0.21\ Mbps$ for $T_2 = 15.12\ Mbps$ (from equation 4)

$t_{drop} = -0.21\ Mbps$ since $t_{increase} = -t_{drop}$

Scenario 2	**Maximum throughput (Mbps)**	**Average throughput (Mbps)**	**Throughput drop (Mbps)**
Case 1	15.53	15.12	0
Case 2	6.04	4.68	10.44
Case 3	9.21	8.65	6.47
Case 4	15.53	15.33	0.21

Table 16. Scenario 2: Maximum and average throughput.

Again, since t_{drop} for case $2 > t_{drop}$ for case 1. As the network load increased from 30 to 113 SSs, there is a corresponding decrease in throughput. In case 2 to 3, single SCBS was integrated with the network. From case 3 to 4, another SCBS was used. Thus, t_{drop} for case $4 < t_{drop}$ for case $3 < t_{drop}$ for case 2. This shows that as the number of SCBSs increases, t_{drop} decreases.

The results of the average values in Table 16 show that the throughput rose from test cases 2 to 3, from $4.68\ Mbps$ to $8.65\ Mbps$ – a 84.83% increase when a single SCBS is integrated with the network. From test cases 3 to 4, the average throughput rose by another 77.23% (from $8.65\ Mbps$ to $15.33\ Mbps$) when an additional SCBS is introduced to the network. The total increase from test cases 2 to 4 amounts to 227.56% when two SCBSs are used.

5.2 Scenario 3: Independently deployed small cell and Wi-Fi analysis

This section comparatively analyses the performance of independently deployed Wi-Fi/LTE small cell, Wi-Fi/WiMAX small cell and Wi-Fi. The aim is to investigate how these small cell networks perform when compared with Wi-Fi using four QoS parameters: email download response time, email upload response time, HTTP page response time and video conferencing E2E delay. The graph in blue colour in this scenario depicts a Wi-Fi network consisting of 30 SSs (test case 1). Test cases 2 and 3 represent the red and light green part, as shown in the respective Figures 29 to 31. The values in Table 18 were obtained by dividing the values of QoS in Table 17 by the least value. For email download response time, all QoS values are divided by 0.110 s.

Table 17. Scenario 3: Summary of average values of QoS parameters.

QoS parameters	**Test case 1: Wi-Fi/WiMAX**	**Test case 2: Wi-Fi/LTE**	**Test case 3: Wi- Fi**
Email Download Response Time	0.110	0.744	0.738
Email Upload Response Time	0.315	0.703	2.086
HTTP Page Response time	2.12	2.800	17.986
Video Conferencing E2E delay	0.012	0.023	0.051

Test cases 2 and 3 represent the red and light green part, as shown in the respective Figures 29 to 31. The values in Table 18 were obtained by dividing the values of QoS in Table 17 by the least value. For email download response time, all QoS values are divided by 0.110s.

Table 18. Ratio analysis of scenario 3.

QoS parameters	**Wi-Fi/Wi-MAX Ratio**	**Wi-Fi/LTE Average**	**Wi- Fi**
Email Download Responce Time	1	6.73	6.71
Email Upload Response Time	1	2.23	6.62
HTTP Page Response time	1	1.32	8.48
Video Conferencing E2E delay	1	1.92	4.25

5.2.1 Email download response time

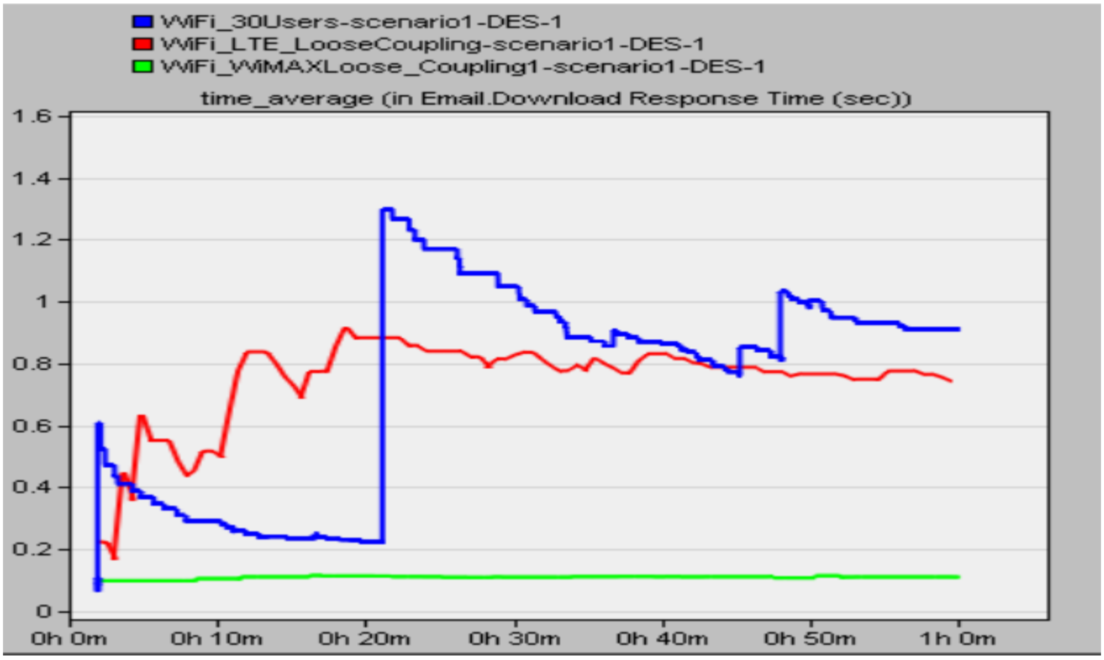


Figure 31. Email download response time for Wi-Fi and small cell network.

The download response time from Table 17 for Wi-Fi/WiMAX independently deployed small cell network is about 0.110 s. From the analysis in Table 18, it is observed that the download response time in a network of Wi-Fi/WiMAX small cell is about seven times faster and outperforms that of Wi-Fi/LTE and the Wi-Fi network.

As shown in Figure 31, a spike occurs at about 20 min of simulation time. There are more email download requests sent from the 30 Wi-Fi SSs to the email server. These requests increase until about 1.3s forming a considerable data spike. Since all download requests cannot be acknowledged at once (due to limited bandwidth), TCP control algorithm (or packet loss) is implemented to manage congestion as earlier explain on page 36.

From about 20 min until approximately 50 min, a decrease in congestion window is observed (satisfying equation 8 and 9). That is, the size of the data spike decreases from bout 1.3s (at 20 min simulation time) to about 1.1s This implies packet loss. TCP uses packet loss to limit data congestion. At about 40 min, re-transmission of packets again starts.

5.2.2 Email upload response time

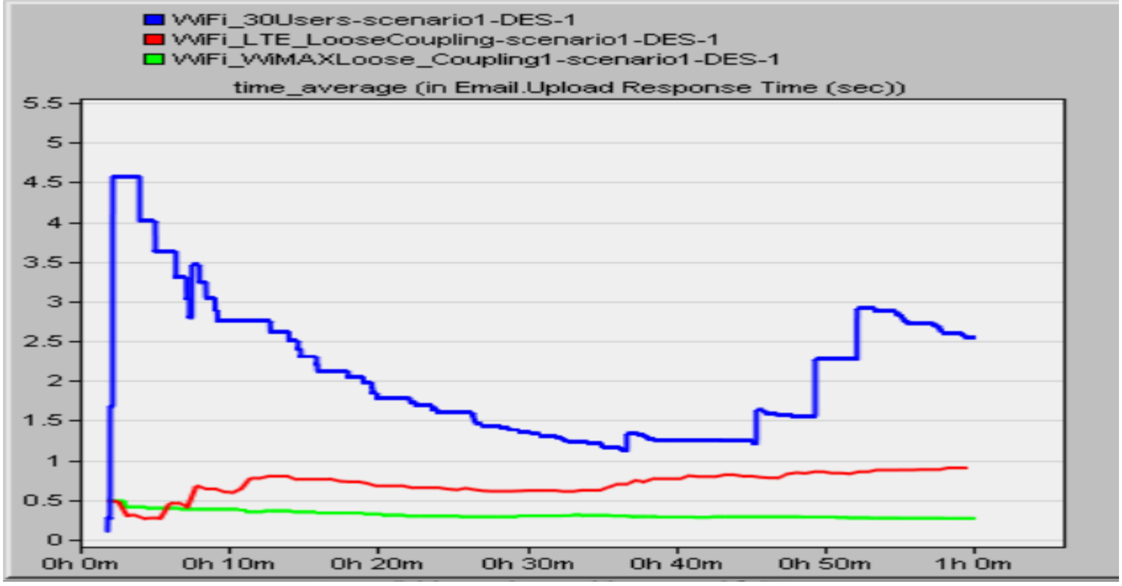


Figure 32. Graph of email upload response time

As shown in Figure 32, the email upload response time of Wi-Fi/WiMAX small cell is about 0.32 s and is approximately 7 times better than that of Wi-Fi/LTE and Wi-Fi network whose email upload response time are highly unstable and are 0.703 s and 2.086 s respectively. The Wi-Fi network is highly unstable.

As earlier explained for Figure 31. The decreasing part of the graph is the TCP control mechanism to limit congestion in the network, and thus, packet loss is implemented. At about 40 min, re-transmission again starts. The Wi-Fi SSs re-send request to the email server. This increase until about 55 min, where slight stability is attained.

5.2.3 HTTP page response time

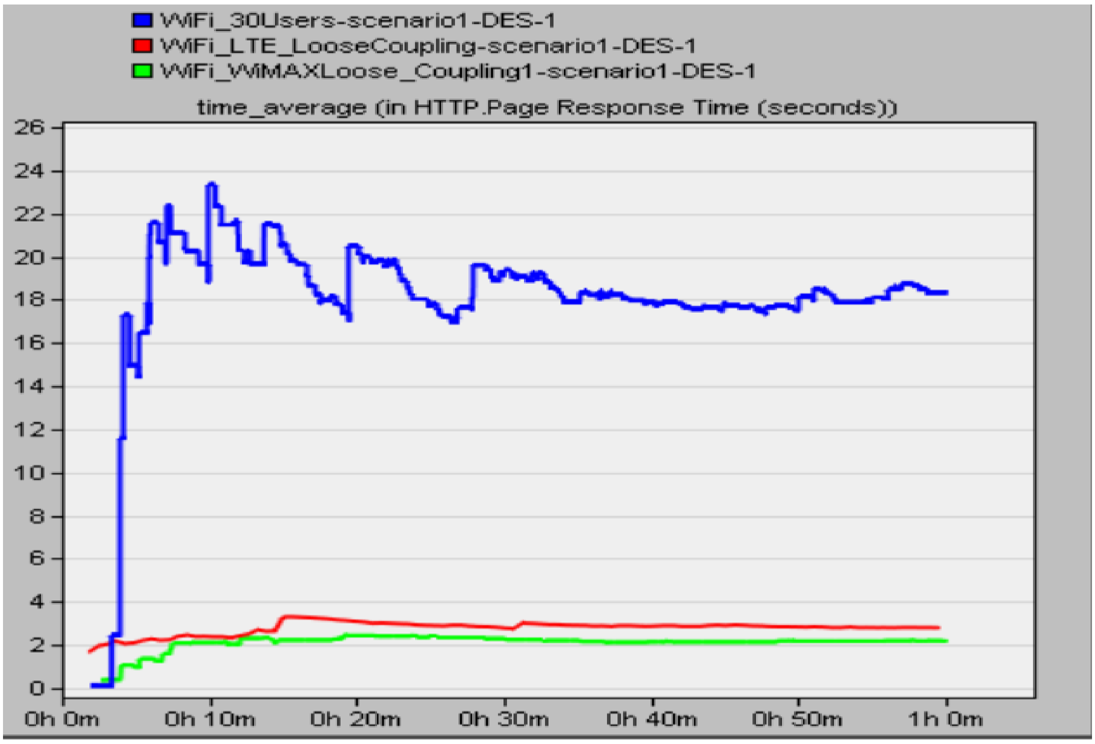


Figure 33. HTTP response time for Wi-Fi, Wi-Fi/LTE and Wi-Fi/WiMAX.

The Wi-Fi HTTP response time is approximately 17,9 s as shown in Figure 33. It reaches slight stability after about 35 min of simulation time. From the ratio test analysis in Table 18, the HTTP page response time for Wi-Fi network is approximately eight times slower than that of Wi-Fi/WiMAX network and Wi-F/LTE network.

5.2.4 Video conferencing end-to-end delay.

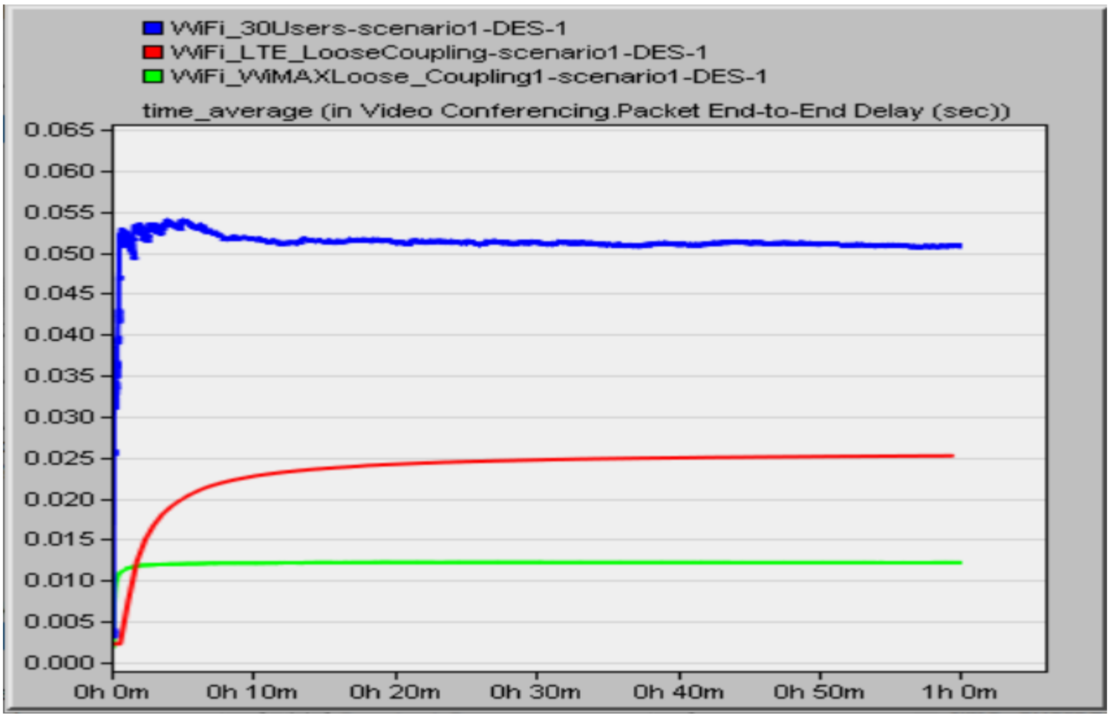


Figure 34. Video conferencing packet E2E delay

The average E2E delay (blue line in Figure 34) for the Wi-Fi network of 30 SSs appears to be constant, and its average value is about 0.051 s. The Wi-Fi/LTE E2E delay in video conferencing reaches a constant value of 0.023 s after about 20 min of simulation time.

The analysis of Table 18 shows that Wi-Fi/WiMAX small cell network video conferencing packet E2E delay is approximately 2 times better than Wi-Fi/LTE network, and its performance surpasses that of Wi-Fi network by about 4 times.

Table 18. Ratio analysis of scenario 3.

QoS parameters	**Wi-Fi/Wi-MAX Ratio**	**Wi-Fi/LTE Average**	**Wi- Fi**
Email Download Responce Time	1	6.73	6.71
Email Upload Response Time	1	2.23	6.62
HTTP Page Response time	1	1.32	8.48
E2E delay	1	1.92	4.25

5.3 LTE downlink throughput analysis

In test cases 1 and 2, the Wi-Fi/LTE small cell composed of only video SSs is compared with similar network consisting of email, HTTP and video uniformly distributed in the network.

In test cases 3 and 4, email and HTTP are separately configured. Thus, Figure 34 is a plot of test cases 1, 3 and 4. Table 19 is a summary of the LTE downlink throughput for all four cases.

Table 19. LTE downlink throughput.

Parameters	**SCENARIO 4**			
	Test Case 1	**Test Case 2**	**Test Case 3**	**Test Case 4**
Average Throughput/Mbps	20.48	6.95	0.15	0.78
Application type	Video	Email HTTP and Video	Email	HTTP
Numbers of Subscriber Stations	30	30	30	30

5.3.1 Scenario 4a: Downlink throughput analysis for cases 1, 3 and 4

The light green line of the graph in Figure 36 illustrates the Wi-Fi/LTE network consisting of 30 video clients (test case 1). The red and blue line depicts a network of email and HTTP SSs – cases 3 and 4, respectively.

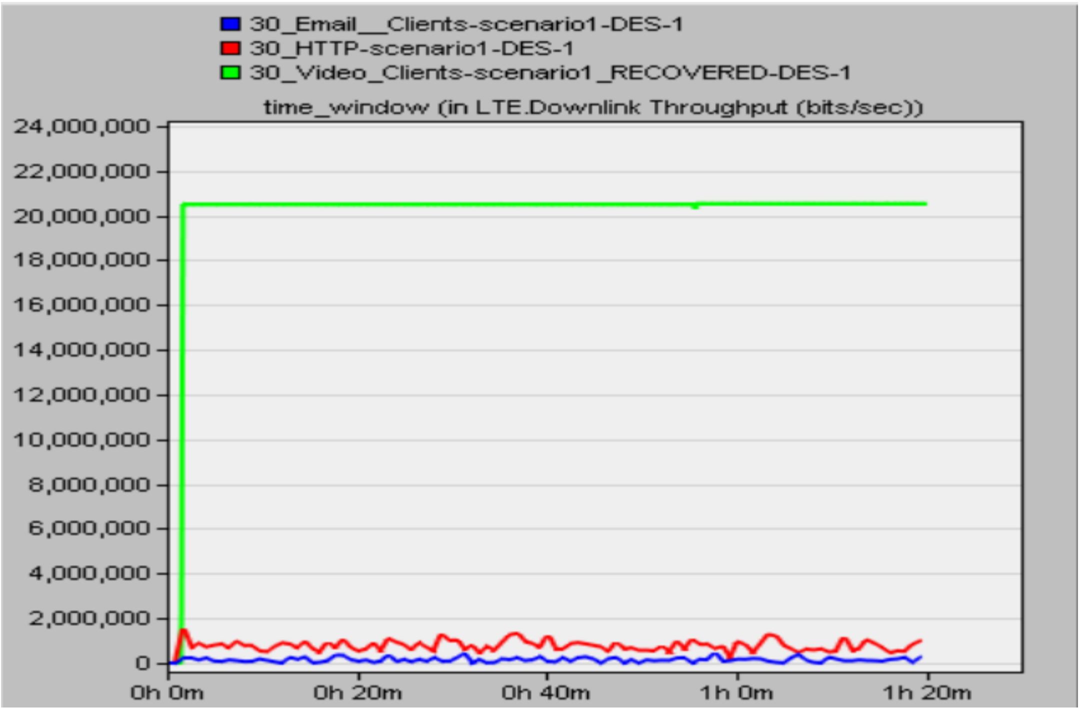


Figure 36. Video, email and HTTP subscriber stations comparison for cases 1, 3 and 4.

After an hour and 20 minutes of simulation time, it is observed that the throughput of the network consisting of 30 video clients surprisingly outperforms that of email and HTTP clients by approximately 13553% and 2525.6% respectively. The graph of email and HTTP clients is further displayed in Figure 37 in the following page.

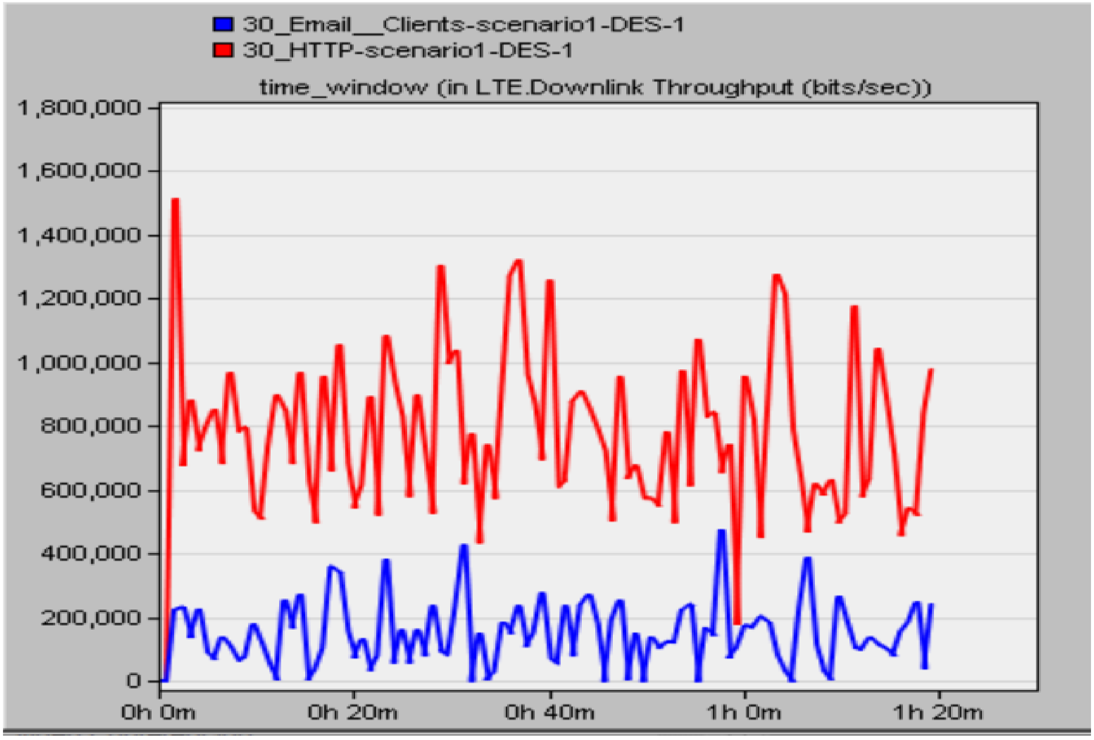


Figure 37. Email and HTTP clients for cases 3 and 4.

Figure 37 depicts test cases 3 and 4. The downlink throughput of the Wi-Fi/LTE small cell with HTTP SSs is better than the network of email clients by about 420%. The average LTE downlink throughput of cases 1 to 4 are shown in Table 19.

5.3.2 Scenario 4b: Throughput analysis for cases 1 and 2

The blue graph in Figure 35 indicates test case 1. The average throughput as seen in Table 19 is approximately 6.95 Mbps. The red line (test case 2) depicts the Wi-Fi/LTE small cell consisting of 30 video conferencing clients. The throughput is found to be 20.48 Mbps. It performs better than the network of a mixture of email, video and HTTP clients by about 194.7%.

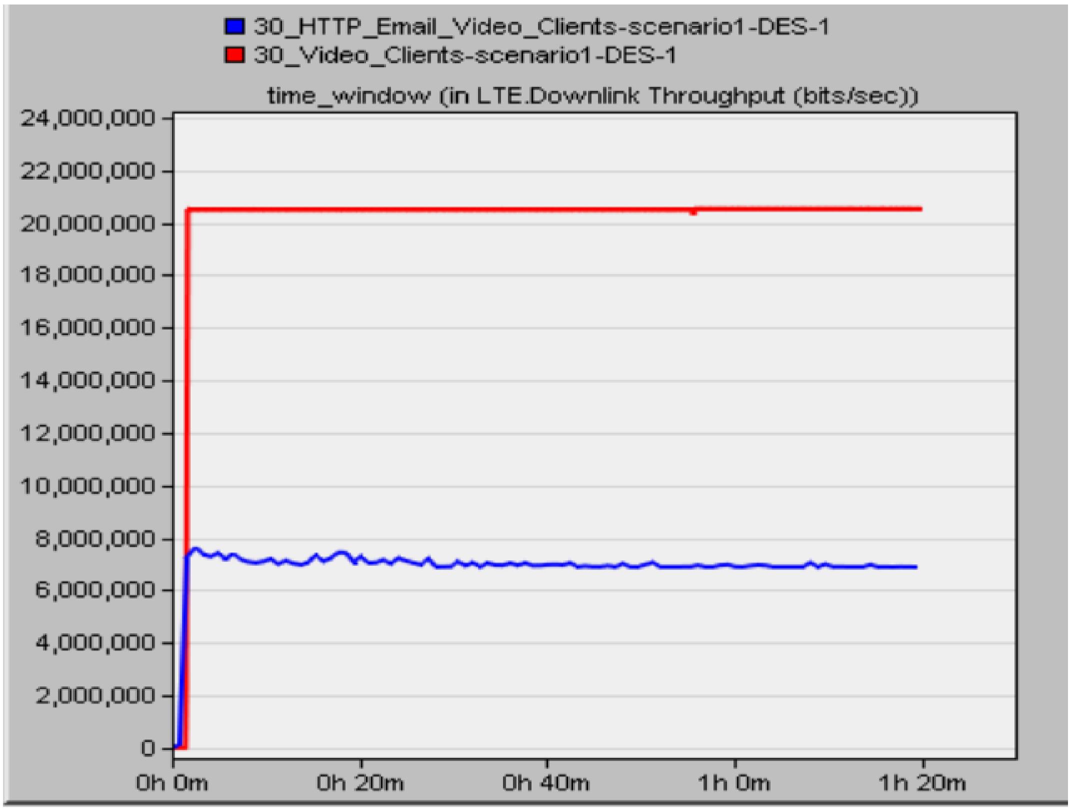


Figure 35. LTE downlink throughput for 30 clients for cases 1 and 2.

6 CONCLUSION

The IEEE 802.11ac was successfully integrated with WiMAX and LTE in a loose coupling architecture. Instead of the conventional macro BS, inexpensive SCBSs were used as independent deployment or integrated with an already existing macro BS. Deductions are briefly summarized below.

- The global throughput of an integrated Wi-Fi and small cell network decreases with the increase in the distance of macro BS from the network.
- The global throughput also decreases with an upsurge in network traffic.
- SCBSs can optimize the throughput of a network and minimize the drop in throughput.
- An integrated network of video SSs of Wi-Fi/LTE small cell achieved a better throughput when compared with a network of HTTP and email SSs.
- The integrated network of Wi-Fi/WiMAX outperforms that of Wi-Fi/LTE and Wi-Fi networks.

In scenario 1, using four test cases in the analysis, it was observed that a small cell could indeed optimize the throughput of the network. For a loosely coupled Wi-Fi/WiMAX network experiencing a drop in the throughput as a result of the location of the macro BS from the network, the integration of a single WiMAX SCBS to a macro BS, increased the throughput by approximately 218.33%. This type of small cell network is especially relevant for indoor locations that may experience a drop in throughput as a result of the location of the network from the macro BS.

It was also proven that when a given network experiences an unprecedented upsurge in data traffic, deployment of SCBSs can boost the network throughput. As demonstrated in scenario 2, the global throughput rose 227.56% by the introduction of two SCBSs.

Thus, in scenario 1, a single SCBS was necessary to optimize the global throughput of the network, while in scenario 2, two SCBSs were needed. Therefore, depending on the level of throughput loss, more SCBSs will be needed to upgrade the throughput fully. Additionally, since SC is highly inexpensive when compared to macro BS, its use represents a potential solution to throughput loss.

The limitation in scenario 1 and 2 is that if throughput for the given network is fully optimized, the addition of more SCBSs will not increase throughout further; instead, throughput is found to decrease. It is more reasonable to use more SCBSs until the global throughput of the network is fully optimized.

In scenario 3, it is observed that Wi-Fi performance is significantly improved when integrated with WiMAX and LTE SCBS. From analysis with the QoS parameters, it was demonstrated that the loose-coupled architecture of Wi-Fi/WiMAX small cell outperforms that of Wi-Fi/LTE small cell and Wi-Fi system. The Wi-Fi/LTE small cell was observed to have a better performance than the Wi-Fi system.

A significant limitation for scenario 3 is that it works properly only for loosely coupled systems. In a tightly coupled system, the Wi-Fi network without integration with LTE or WiMAX is observed to performs better than Wi-Fi/LTE small cell. Thus, the small cell network of Wi-Fi/LTE have lesser performance in QoS analysis when compared to the Wi-Fi system.

In scenario 4, The Wi-Fi/LTE small cell network achieved a substantial rise in downlink throughput in a network consisting of video subscriber station when compared to a network of a mixture of email, HTTP and video conferencing SSs. That is the network consisting of video clients in a Wi-Fi/WiMAX small cell loose coupling architecture maintain a surprising surpassing performance over email and HTTP clients by approximately

13553% and 2525.6% respectively. Therefore, the Wi-Fi/LTE small cell network has a higher capacity when only video application is run. When the same network is running other applications (HTTP, video conferencing and email) concurrently**,** the throughput significantly drops. Therefore, during an unprecedented upsurge in network loads, limiting some of the networks to run a single video application, will enable better utilization of bandwidth and hence a higher throughput can be achieved.

Handover delay analysis of Wi-Fi and LTE small cell integration in loose coupling architecture is one suggested areas of future research. Ultra-dense network and a large number of SCBSs as proposed by Qualcomm may be used. (Rising to Meet the 1000x Mobile Data Challenge – Qualcomm: Wireless Technology and Innovation, 2012).

Another potential future work will be Wi-Fi/LTE-5G small cell integration. When the Wi-Fi network integrated to work with a 5G small cell in unlicensed spectrum, interference mitigation should be taken into consideration. Wi-Fi (IEEE 802.11ac) has the lowest performance in QoS in scenario 3 of the analysis in this thesis; thus, the Wi-Fi 6 (IEEE 802.11ax) may be considered to boost the home Wi-Fi performance and optimize further its throughput and QoS.

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