A COMPARATIVE INVESTIGATION ON THE APPLICATION AND PERFORMANCE OF FEMTOCELL AGAINST WI-FI NETWORKS IN AN INDOOR ENVIRONMENT

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DECLARATION

I declare that this research report is my own unaided work. It is being submitted for the Degree of Master of Science to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

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ABSTRACT

Due to the strenuous demands on the available spectrum and bandwidth, alongside the ever increasing rate at which data traffic is growing and the poor quality of experience (QoE) faced with indoor communications, in order for cellular networks to remain dominant in areas pertaining to voice and data services, cellular service providers have to reform their marketing and service delivery strategies together with their overall network architecture. To accomplish this leap forward in performance, cellular service operators need to employ a network topology, which makes use of a mix of macrocells and small cells, effectively evolving the network, bringing it closer to the end-user.

This investigation explores the use of small cell technology, specifically Femtocell technology in comparison to the already employed Wi-Fi technology as a viable solution to poor indoor communications. The performance evolution is done by comparing key areas in the every day use of internet communications. These include HTTP testing, RTP testing and VoIP testing. Results are explained and the modes of operation of both technologies are compared.

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Finally, I would like to thank my parents, my siblings Tonye, Soowuna, Ibiere, Basoene and my nephew Damiete whose faith, friendship and love gave me the courage to take on this challenge. Thank you for loving in me.

DEDICATION

To my Family

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LIST OF ABBREVATIONS

1G – First Generation
2G – Second Generation
3G – Third Generation
3GPP – Third Generation Partnership
4G – Fourth Generation
ACK – Acknowledgement
ACS – Auto Configuration Servers
AP- Access Point
BS – Base Station
BSC – Base Station Controller
BSS – Base Station System
BSS – Basic Service Set
BTS – Base Transceiver Stations
CAC – Call Admission Control
CCK – Complementary Coding Keying
CDF – Cumulative Distributed Function
CDMA – Code Division Multiple Access
CPE – Customer Premise Equipment
CSMA/CA - carrier sense multiple access protocol with collision avoidance
CSS – Cisco Consulting Service
DDoS – Distributed Denial of Service
DiffServ – Differentiated Services
DL – Download
DoS – Denial of Service
DPDCH – Dedicated Physical Data Channel
DS – Distribution System
DSL – Digital Subscriber Line
EAP – Extendable Authentication Protocol
ESS- Extended Service Set
EV-DO – Evolution Data Optimized
FAP – Femtocell Access Point
FCC –Federal Communications Commission
FCS – Femtocell Convergence Server
FDMA – Frequency Division Multiple Access
FDMA – Frequency Division Multiple Access
FGW – Femtocell Gateway
FMS – Femtocell Management System
FNG – Femtocell Network Gateway
FSeGW – Femtocell Security Gateway
G-MSC – Gateway Mobile Switching Center
GGSN – Gateway GPRS Support Node
GPRS – General Packet Radio Service
GSM – Global System for Mobile Communication

GUI – Graphic User Interphase
HD – High Definition
HNB – Home Node B
HNBGW – Home Node B Gateway
HSPA – High Speed Packet Access
HSUAP – High Speed Uplink Packet Access
HTTP – Hypertext Transfer Protocol
IBSS – Independent Basic Service Set
ICASA – Independent Communications Authority South Africa
ICMP – Internet Control Message Protocol
ICNIRP – International Commissions on Non-ionising Radiation Protection
IEEE - Institute of Electrical and Electronics Engineers
IETF – Internet Engineering Task Force
IMT – International Mobile Telecommunications
IMT-A – International Mobile Telecommunications Advanced
IntServ – Integrated Services
IP – Internet Protocol
IPS – Intrusion Prevention System
IPSec – Internet Protocol Security
ISM – Industrial, Scientific and Medical
ISP – Internet Service Provider
ITU – International Telecommunications Union
ITU-R – International Telecommunications Union-Radio
LAN – Local Area Network
LLC – Logical Link Control
LTE – Long Term Evolution
LTE-A – Long Term Evolution Advanced
MIMO – Multiple-Input Multiple-Output
MOS – Mean Opinion Score
MS – Mobile Station
MSC – Mobile Switching Center
OFDM - Orthogonal Frequency-Division Multiplexing
PCS – Personal Communications Service
PDSN – Packet Data Serving Node
PDV – Packet Delay Variance
PLR – Packet Loss Ratio
PSTN – Public Switched Telephone Network
QoE – Quality of Experience
QoS – Quality of Service
RSS –Received Signal Strength
RSVP – Resource Reservation Protocol
RTCP – Real-time Transport Control Protocol
RTP – Real-time Transfer Protocol
RTT – Round Trip Time

SAE – System Architecture Evolution
SGSN – Serving GPRS Support Node
SGSN – Serving GPRS Support Node
SIFS – Short Inter-frame Space
SIM – Subscriber Identity Module
SNR – Signal to Noise Ratio
SOHO – Small-Office Home-Office
TCP – Transmission Control Protocol
TDMA – Time Division Multiple Access
U-NII – Unlicensed National Information Infrastructure
UDP – User Datagram Protocol
UHF – Ultra High Frequency
UMTS – Universal Mobile Telecommunications System
URl – Uniform Resource Locator
USB – Universal Serial Bus
UTP- Unshielded Twisted Pair
VNI – Visual Networking Index
VoIP- Voice over Internet Protocol
VPN – Virtual Private Network
W-CDMA – Wideband Code Division Multiple Access
WAN – Wide Area Network
WAP – Wireless Access Point
WAP – Wireless Access Point
WEP – Wired Equivalency Privacy
Wi-Fi – Wireless Fidelity
WiBro – Wireless Broadband
WiMAX – Worldwide Interoperability for Microwave Access
WLAN- Wireless Local Area Network

1. Introduction

With the wide spread of new age devices equipped with network adapters that can access both cellular and Wi-Fi networks, cellular service providers may look at this as an opportunity to alleviate their already congested network through the use of small cell technology. Cellular service providers are faced with the ever-increasing demand for mobile broadband services and also the poor quality of indoor communication due to reduced signal strength. The introduction of small cells aim to tackle these challenges by bringing the network closer to the user. These small cells also known as home base stations (BS), are low- power base stations operating in a licensed spectrum from inside the end-users premises, offering improved indoor coverage with increased performance. They function with the operator’s approval to offer enhanced voice and broadband services in a low-cost technology agnostic form. They utilize the already existing IP network in the indoor environment as the backhaul architecture to access the cellular core network. Indoor data traffic could be routed into the cellular network using a nearby small cell site, leaving the corresponding user to experience an increase in voice and data service capacity while in addition sparing the macrocell base station resources, which in turn implies a reduction in network maintenance and deployment costs for the cellular network operator.

For this investigation, the small cell technology known as Femtocell will be compared to the already employed Wi-Fi technology to see which performs better under varied transmission conditions. A Femtocell could be broadly defined as a home base station or a cellular network access point that connects standard mobile devices to a mobile operator’s network using residential DSL connection. Femtocell technology either currently being used under 3G specifications or as part of a future LTE roll out scheme have attracted huge interest from both mobile operators looking for new areas of commercial revenue in lieu of the reducing satisfaction and unappealing Quality of experience (QoE) traditional cellular networks provide, and from end-users eager to significantly upgrade voice and data communications made indoors with the added quality of service (QoS) guaranteed by networks operating in a licensed spectrum. But on the other hand, Wi-Fi networks are already vastly deployed and can conveniently provide voice and data services. The exploration of both technologies in the subsequent chapters would reveal both triumphs and shortcomings of these technologies in an attempt to answer the key research question “Do we need Femtocells when there is Wi-Fi technology?”

1.1 Summary of research Report

This research report is divided into five chapters and a list of references and appendices. Chapter one gives a brief introduction into the subject matter while chapter two is the literature survey. Chapter two begins with the introduction to wireless network communications, establishing operational principle and the architecture of both cellular and Wi-Fi technology along with the technical issues and considerations that must be observed when choosing one technology over the other. This second chapter further reviews the evolution of cellular network technologies over the years starting with the first generation of cellular technology in the early 1980s to the now imminent fourth generation. This chapter also delves into the standardization of Wi-Fi technology and the frequency bands that it operates in. it also discusses the introduction of Femtocells in the industry as a means to reduce the challenges mobile service operators are faced with when it comes to indoor signal strength and also as a way to offload data traffic from the macrocell network. This chapter also compares the key aspects of both technologies and concludes with a view of Femtocell deployment in South Africa.

Chapter three serves as a basic introduction to the subject of Femtocells vs. Wi-Fi technology, and validates the need for this investigation by providing an overview of the problem statement, the objectives of the research and the methodology used in the experimentation that investigate the problem. It also includes the previous work done on the subject matter, stating the research efforts that have already been put into the investigation of the performance capabilities of Femtocells against Wi-Fi.

Chapter four begins with an introduction into the experimentation procedures and the scenarios the experiments will be conducted in. Preliminary assumptions are stated and base line testing conducted to establish control parameters for subsequent test results. Testing areas are be further investigated (HTTP, RTP and VoIP). The evaluation of all tests are stated, with results described, summarized and collected. Key findings, observations and conclusions of all testing are stated as well. Chapter five provides an overall conclusion to the investigation. This chapter revisits the intent of the research to ensure all objectives and the key research question and sub questions have been sufficiently answered. It concludes the overall research with recommendations and potential future research topic in Femtocell and Wi-Fi.

2. Introduction to Wi-Fi and Cellular networks

2.1 Wi-Fi

Wi-Fi Wireless communications are achieved through a network in which electronic devices connect to a larger network infrastructure via a wireless link at the network edge. This network is known as the *802.11 Wireless Local Area Network* (WLAN) or Wi-Fi network. Wi-Fi is the technology that allows these electronic devices such as computers, tablets, mobile phones, media players and cameras to connect at high speeds to the larger network infrastructure all without the need for an actual physical wired connection.

The term *Wi-Fi* is an acronym for wireless fidelity. It was coined in 1999 by the Wi-Fi Alliance - the organization that owns the registered trademarked phrase "Wi-Fi", due to its similarity to the then well-known phrase "hi-fi" [1]. The Institute of Electrical and Electronics Engineers (IEEE) defines wireless local area network (WLAN) as "*a data transmission system designed to provide location-independent network access between computing devices by using radio waves rather than a cable infrastructure in accordance to the 802.11 standard*"[2].

2.1.1 802.11 Specification and comparison

This 802 standard refers to a group of specifications developed by the IEEE. Designated by a Dewey Decimal-like system, the 802 standard differentiates between various technology families. For instance, 802.11 is a sub-standard of the 802 family that identifies technology that has an over-the-air interface between a base station (BS) and a wireless end node. Products that use Wi-Fi technology fall under this 802.11 specification, and are then further identified by a lower case alphabet that classifies which particular technology is in operation, for example 802.11g [3].

There are four dominant generations of Wi-Fi products (a, b, g and n). Each generation is defined by a set of characteristics that relate to frequency, bandwidth and performance.

Wi-Fi Technology series	**Frequency band used**	**Bandwidth or maximum data rate**	**Key features**
802.11a	5.1 – 5.8GHz	54Mbps	• Uses orthogonal frequency-division multiplexing (OFDM) • Uses a more efficient coding technique that splits that radio signal into several sub-signals before they reach a receiver
802.11b (also referred to as "802.11 High Rate")	2.4 – 2.485GHz	11Mbps	• Slowest and least expensive standard • Can handle up to 11Mbps (and is capable of falling back to 5.5, 2 and 1-Mbps) • Uses complementary code keying (CCK) modulation to improve speeds.
802.11g	2.4 – 2.485GHz	54Mbps	• Uses orthogonal frequency-division multiplexing (OFDM) • Used for transmission over short ranges • Hardware is fully backward compatible with 802.11b equipment
802.11n	2.4 GHz, 5 GHz, 2.4 or 5 GHz (selectable), or 2.4 and 5 GHz (concurrent)	450Mbps	• Builds upon previous standards by adding ***m**ultiple-**i**nput **m**ultiple-**o**utput* (MIMO). • Additional transceiver antennas allow increased data throughput and range through spatial multiplexing and diversity • Uses Alamouti coding Schemes.

Table 1. Wi-Fi 802.11 series [1]

Besides these differences in key features shown in table 1, these four 802.11 standards share many similar characteristics; they all use the same medium carrier sense multiple access protocol – with collision avoidance (CSMA/CA), they all use the same frame structure for their link layer frames, they all can reduce transmission rates in order to cover greater range and all four standards can operate in "infrastructure mode" and "ad hoc mode" as will be discussed later in this chapter.

The 802.11b WLANs have a data rate of 11Mbps and operate in the frequency band of 2.4 – 2.485 GHz, the same frequency spectrum as 2.4GHz phones, baby monitors, Bluetooth and microwave ovens. 802.11a WLANs operate at a higher Bit rate (54Mbps) and frequency (5.1 – 5.8GHz) but have a shorter transmission range for a given power level. 802.11g WLANs operate in the same frequency band as 802.11b (2.4 – 2.485 GHz) and is backward compatible. This means 802.11b clients may be upgraded to 802.11g with no problems [1]. 802.11n defines modifications to the 802.11 physical layer so that modes of operation can be enabled which are capable of much larger throughputs, with the highest throughput of at least 450 Mb/s. This is achieved by the use multiple-input multiple-output (MIMO) antennas, this means two or more antenna both on the sending and receiving sides, transmit and receive different signals independently, allowing increased data throughput and range [6].

2.1.2 Wi-Fi Architecture and Hierarchy

The major benefit users acquire from wireless LANs (WLANs) is the increased mobility. With WLAN being an extension of conventional terrestrial local area networks (LAN), network users can move about without restrictions and access LANs from anywhere within the wireless network perimeter. WLANs provide freedom to users from a reliance on physical-wired access to the network backbone thus providing anytime and anywhere network access.

Each device on the wireless LAN is referred to as a *wireless host* or *node* in the 802.11 specification. Wireless hosts or nodes are the end-system devices that run applications, for example, laptops, tablets, smart phones or desktop computers. For a host to connect to a LAN with no physical-wired connection, it needs a wireless transmitter or wireless network adapter. This adapter ensures connectivity between the device and the wireless access point (WAP) or wireless router. This connectivity may be referred to as the *wireless link* [4]. Wireless hosts connect to a WAP through the various wireless communication standards. Figure 1 depicts the different wireless standards and the different rates and distances each standard can transmit over.

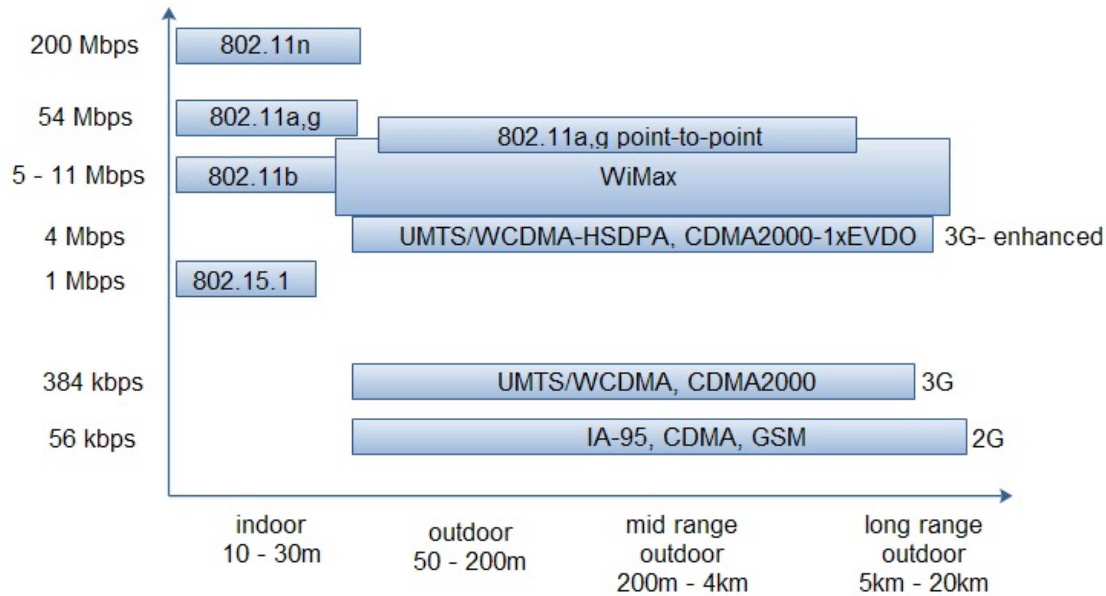

Figure 1. LInk characteristics of selected wireless network standards [4]

The WAP may be considered to be the foundation of a Wi-Fi wireless network as its principle function is to receive information (also known as data packets) from the Internet via a broadband connection and then convert this information into radio waves, which it then broadcasts as a wireless electromagnetic signal, thus creating a small local area around which wireless electronic devices (wireless hosts) with an installed wireless network adapter can detect and tune into if within range. A WAP is often responsible for coordinating the transmission of several end-system nodes with which it is associated with. The process of sending information back to the Internet works the same way but in reverse; the device sends information via a radio signal to the wireless access point, which then converts the signal and then transfers it back via the broadband connection.

It is important to note that this wireless electromagnetic signal loses intensity as the device is moved further away from the WAP. This means the quality of the connection decreases as the device is placed further away from the source, resulting in decreased signal strength [4].

Figure 2 below illustrates the main architectural components of a WLAN. The fundamental building blocks of the 802.11 architecture are the Basic Service Set (BSS), the wireless access point (WAP), wireless network adapter and several wireless hosts.

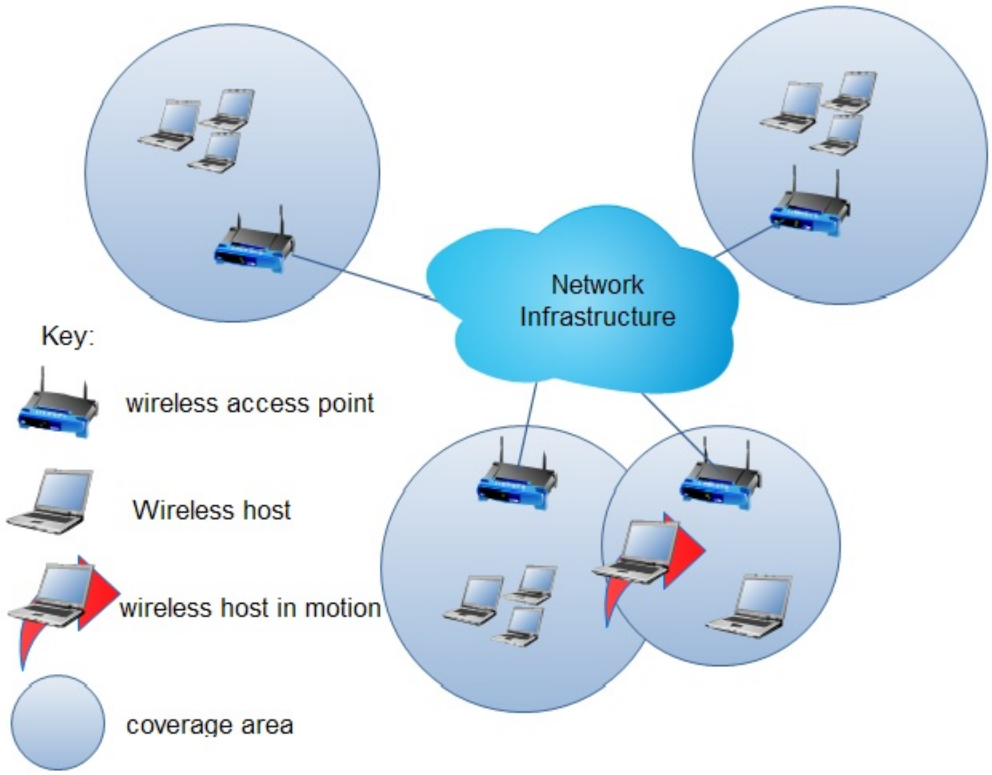

Figure 2. Elements of a wireless network copied from [4]

In the elements of a wireless network shown in figure 2, the WAP is connected to the larger network infrastructure directly through a wired Ethernet connection, thus operating as the link between the wireless host and the larger community in which the host communicates with. The WAP provides wireless connection using radio frequency links for other devices to utilize that wired Ethernet connection.

When two or more hosts connect in order to communicate with each other, they construct a Basic Service Set (BSS). The smallest BSS may consist of a minimum of two hosts. Hosts associated with a BSS are often referred to as operating in “infrastructure mode”. This is due to all conventional network services being provided the larger network with which the wireless host connects with via the WAP. This larger network is referred to as the “infrastructure network”.

A stand-alone BSS that is not connected to a WAP is referred to as an Independent Basic Service Set (IBSS) or the more commonly known “Ad-Hoc Network”. This network is one where the hosts communicate only peer to peer i.e. to each other, no infrastructure with which to connect, no central control and no connection with any outside networks. Due to the absence of such infrastructure, the hosts must provide for network services independently. Here network is formed on-the-go by wireless hosts located in close proximity to each other that need to communicate. This ad-hoc network architecture (depicted in figure 3) has no preexisting network infrastructure in its location but communicates wirelessly through end node signal transmission.

3. Ad-Hoc network copied from [4]

Coverage in larger areas may require several interconnected BSS’s with overlapping signals. When several BSS's interconnect, they do so using a *Distribution System* (DS). A distributed system could be defined as *a “mesh of networks that consist of a collection of independent nodes linked by a local area network and equipped with distributed system software that enables these nodes to coordinate activities and share resources such as system hardware, software, and data”* [5].

Employing a DS increases network coverage by allowing the WLAN to be extended through the use of several WAPs, so each BSS becomes a section of an extended, wider network. Thus, movement of data between the DS and the BSS is accomplished only with access to the DS via a WAP. When a wireless host moves beyond the range of its associated WAP into the range of another WAP, its point of attachment in the DS also changes. This process is referred to as "handoff" or "handover"[2].

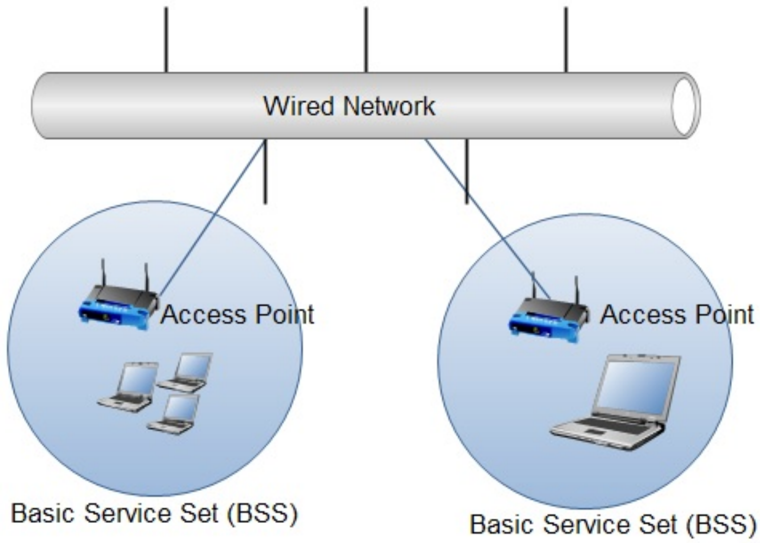

Figure 4. ESS network copied from [2]

The next level in the WLAN hierarchy is the Extended Services Set (ESS). This is the combination of large and complex interconnected networks using BSS's and DS's. With each BSS consisting of a single WAP and several nodes, the entire ESS appears as one solitary BSS to the logical link control layer (LLC). This is rather advantageous to the WLAN user as each host within the ESS can communicate and move between BSS's transparently. This ESS network architecture also known as "*the multiple cell*" architecture is depicted in figure 4.

2.1.3 Wi-Fi Support

The Wi-Fi Alliance defines a Wi-Fi product as "any *wireless local area network (WLAN) product that is based on the Institute of Electrical and Electronics Engineers' (IEEE) 802.11 standards*"[1]. Simply put, this means that a Wi-Fi product is one that adheres to any one of the IEE 802.11 standards stipulated in table 1.

The IEEE 802.11 standard focuses on the data link layer and physical layer of the ISO model as depicted in figure 5. This means any LAN protocol or network operating system will operate on an 802.11 compatible WLAN as easily as it would operate over the preexisting IEEE 802.3 Ethernet network standard which laid the foundation for the physical and data link layer technology for LANs.

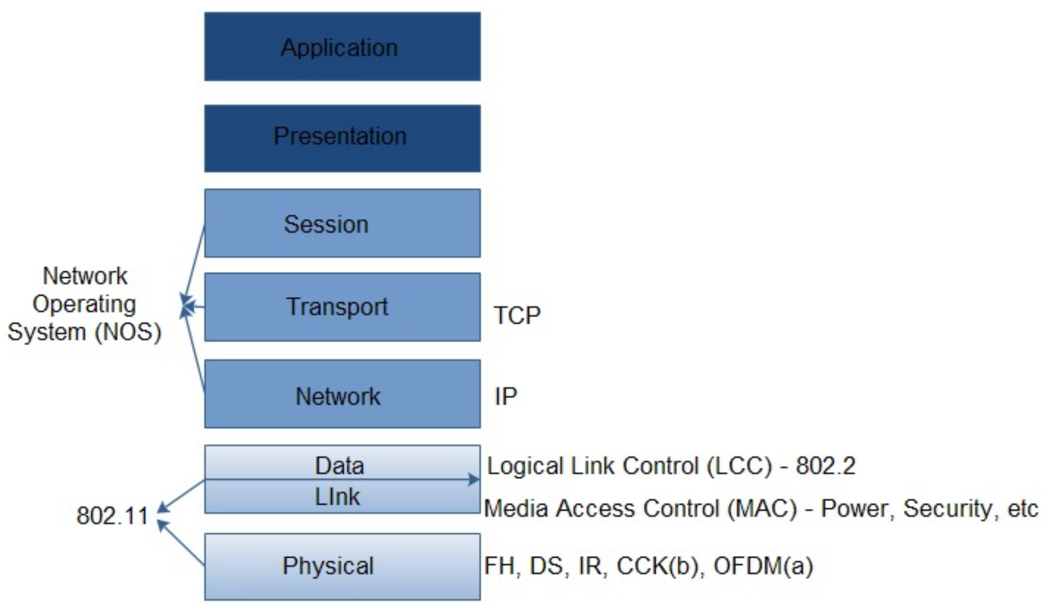

Figure 5. IEEE 802.11 and ISO model copied from [2]

Wi-Fi is supported by a wide selection of devices and applications such as video gaming consoles, smart phones, home networks and various consumer electronics. These products are tested and given the “Wi-Fi Certified” stamp of approval by the Wi-Fi Alliance. Certified products are considered to be interoperable with each other despite being manufactured by different companies. For instance, a user with a Wi-Fi Alliance certified product might use any brand of Wi-Fi certified access points, because they’ve both been Wi-Fi certified. Although the brands may differ, communication between them is made possible because certified products would have passed the Wi-Fi Alliance certification tests and thus operate under the Wi-Fi Alliance approved radio frequency band used i.e. the 5GHz band used for 802.11a and the 2.5GHz band for 802.11b/g/n [1].

2.1.4 Radio frequency bands (5 GHz and 2.5 GHz) for Wireless Networks

Data packets in a Wi-Fi network are transmitted over either a 5GHz or a 2.5GHz frequency band. Networks that utilize the 5GHz frequency band for transmission are not as widely used as the 2.5GHz band networks. This is mostly due to economic factors as the 5GHz equipment is more expensive to deploy. This has made 2.5GHz networks an easy choice for many end-users, which in turn has allowed 2.5 GHz networks to become the well established industry standard. Although the 2.5 GHz band is the prevalent choice for data transmissions for 802.11b/g/n, in order to get the best performance from these standards, 5GHz networks should be considered due to certain 2.5GHz band drawbacks that will be explained further in this section.

- The 2.5GHZ WLAN

The 2.5 GHz band comprises of 14 channels, each with a bandwidth of approximately 20 to 22 MHz and operate in the industrial, scientific and medical (ISM) band. Due to the mass adoption of the less expensive 2.5GHz WLAN, it has inevitably become densely populated as the number of wireless networks and network users have grown. This growth leads to a large number of signal conflicts and interference, as a result of the high amounts data of traffic, access points, and network cards.

To supplement the overcrowding of 2.5GHz networks is the mass adaptation of the newer smart cell phones and wireless devices (iPhones, BlackBerry and Android phones). These smart devices access Wi-Fi 2.5GHz networks for Internet browsing further adding to the stress of the network.

The 2.5GHz network is also mostly unregulated. This means that high-powered antennas and network cards can negatively affect nearby networks [7]. The 2.5 GHz spectrum is shown below in figure 6.

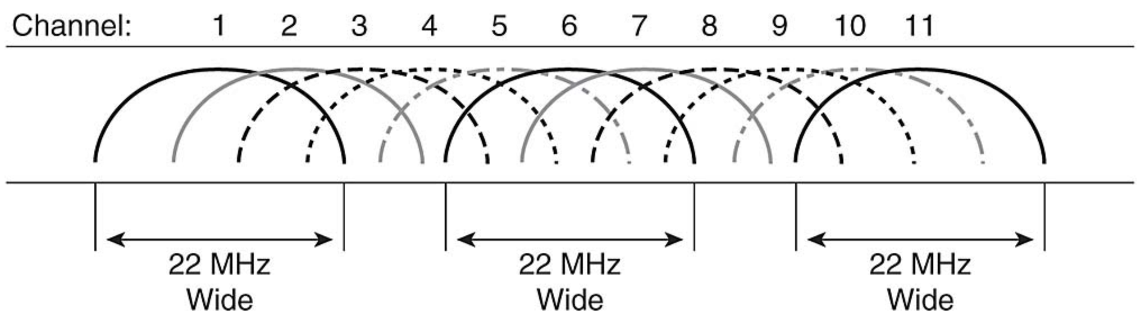

Figure 6. 2.5 GHz Wi-Fi Channel Copied from [8]

- The 5GHZ WLAN

The 5GHz band comprises of 13 channels, each with a bandwidth of approximately 20 MHz operating in the (Unlicensed National Information Infrastructure) U-NII band. The 5GHz frequency band wireless networks can offer relief from the overcrowding of 2.5GHz. It has a clear signal and more channels that can be combined for higher speeds. Due to the lack of users on the 5GHz network, it does not suffer the overcrowding that 2.5MHz networks do. Currently 5GHz networks have less traffic through lower usage and can handle higher data traffic more efficiently because it operates in a larger spectrum with more non-overlapping channels. Each channel has 20MHz of bandwidth that allows for much better speeds compared to the 2.5GHz that is only 80MHz wide. Although the 5GHZ band has the advantages of a clearer signal, non-overlapping channels and is faster than the 2.5GHz band, there are some drawbacks to consider when migrating to a 5GHz wireless network.

One of these drawbacks is that the higher the frequency of a wireless signal, the shorter its range. This leaves the 2.5 GHz networks able to cover a substantially larger range than the 5GHz wireless networks.

Another drawback is that 5GHz networks do not penetrate solid obstacles such as walls and floors as well as the 2.5 GHz signals do. This attenuation concern can limit an access point's reach inside SOHO buildings where several walls may come between a wireless access point and the end-user device.

A key disadvantage of the 5GHz band is that 5GHz equipment is not compatible with 2.5GHz equipment. This is a major drawback as upgrading a current large wireless network installation will mean all previous equipment will be rendered obsolete or all installed components of the network have to be dual band capable (accessible by 2.5GHz and 5GHz). This is not the only issue with the 5GHZ equipment as cost is another drawback. As the popularity of 2.5GHz grows, 2.5GHz wireless network components such as access points, antennas and network cards become easily available and inevitably costs less than the 5GHz components [7].

2.1.5 Wi-Fi Issues and Technical considerations

- Interference:

Considering the two signaling frequencies used by Wi-Fi networks (2.5GHz and 5GHz), any other electronic device operating at these same frequencies will cause interference in a WLAN. With the 802.11b/g functioning in the 2.5GHz band comprising of 14 channels each with a bandwidth of approximately 20 to 22 MHz operating in the ISM band and the 802.11a/n functioning in the 5GHz band comprising of 13 channels each with a bandwidth of approximately 20 MHz operating in the (Unlicensed National Information Infrastructure) U-NII band, interference with other devices is likely to occur.

The ISM and U-NII bands often have devices using the same 2.5GHz and 5GHz frequencies in close proximity to WLANs, making the frequencies crowded. For example, common everyday equipment such as microwave ovens, garage door openers and baby monitors all operate in the 2.5GHz band making WLANs operating at the same frequency experience interference when transmitting. Currently, the 5GHz band allows more data to be carried and is less crowded than 2.5 GHz band, but this is likely to change as the wireless market continues to grow. Although recent WLAN technologies are designed to resist these types of interference, it is sometimes unavoidable [7].

- Data Rate and Throughput

In 802.11 wireless networks, throughput is weakened by protocol overhead, transmission collisions, short inter-frame space interval (SIFS) and retransmissions. The average throughput of each Wi-Fi parameter is about half the peak data rate.

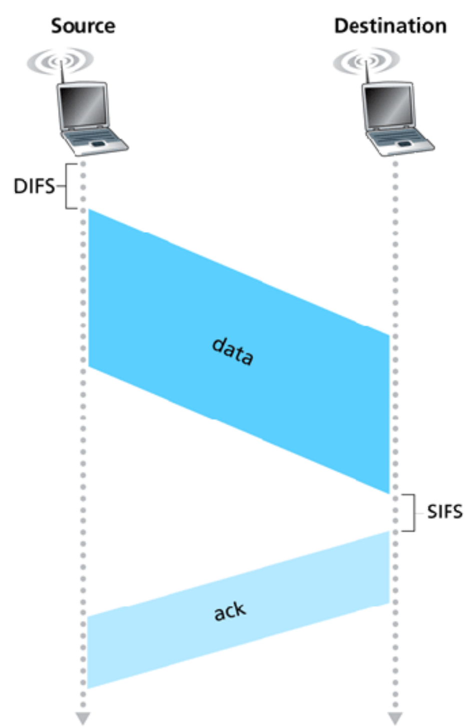

Figure 7. 802.11 link layer ACK copied from [4]

This is caused by the overhead of 802.11 packets as each packet requires a positive and timeous link-layer acknowledgement (ACK) for each frame transmitted as well as accommodating the time elapsed between transmitting the packet and receiving the ACK as seen in figure 7. Unlike the wired Ethernet network where the probability of interference is relatively low, the 802.11 WLAN anticipates a higher chance of interference due to crowded frequencies, thus more overhead is required to face this challenge [4]. The 802.11 standard also allows for the selection of transmission speed so that a less than favorable or weak strength of the received signal (i.e. the information being transmitted) may be overcome by using slower data rates.

This function of the 802.11 standard is very important because the assessment of the throughput required for any particular application is a prerequisite to any decisions being made about which standard to use. Although low data rates are inadequate for most WLAN applications, throughput requirements may be satisfied by the relatively slower speed of the 802.11b standard [1].

- Regulations and Licensing:

Spectrum assignment and operational limitations for WLANs are not consistent worldwide. Governments administer the radio transmission rules, including those used by WLANs. Licensing rules for WLANs must be defined as simply as possible, so that they enable flexible use of Wi-Fi by network operators as well as end-users. It is important to choose products that adhere to these regulations set by the government of the country in which they operate.

Most WLANs operate in the ISM band and do not require the end user to obtain a license to use the spectrum. This lack of licenses and regulations means the Wi-Fi networks do not guarantee any quality of service (QoS) level. The 802.11 Wi-Fi provides only four basic QoS states - Best Effort, Video, Voice, and Background. Since Wi-Fi operates in an unlicensed spectrum, it is ultimately difficult to predict the interference and traffic load due to non-operator deployed access points being used. Hence, Wi-Fi access points are better suited for best effort applications that do not possess high QoS standards [9].

- Security:

Wi-Fi access points typically default to an encryption-free mode. This default configuration provides no form of wireless security, leaving the LAN susceptible to various types of malicious attacks such as malware infestation, spyware malware, denial-of-service (DoS) attack, Distributed DoS (DDoS), packet sniffing, man-in-the-middle attacks and IP spoofing [4]. To stop a network from being accessed by unwanted hosts, WLAN security needs to be integrated into an overall network security strategy. For any employed strategy to be successful, it must conform to three goals: mutual authentication, private communication and data integrity.

The aim of mutual authentication is to ensure end-point authentication i.e. make sure that both the end-user device and WAP are who they say they are. This allows the users to determine with guaranteed assurance, where a packet originates. The aim of private communication is to address the challenge of sending information through open space, which is accessible to everyone. Strong encryption algorithms and dynamic key derivation strategies resolve this issue. The aim of integrity is to make sure that the data is intact when it is received. The Wired Equivalency Privacy (WEP) security is a good example of WLAN security that meets these three goals but a user may implement network layer encryption such as IPSec across both wired and wireless portions of the network thus eliminating the need to have WEP security in place [2].

- **Decreasing signal strength:**

In Wi-Fi networks, it has been established that the host receives a transmitted signal from the WAP, but this electromagnetic signal is a combination of a degraded form of the original signal transmitted by the sender and interference caused by background noise (from other devices operating at the same frequency) in the environment. This is due to multipath propagation and the effects of attenuation on electromagnetic radiation. Multipath propagation occurs when the electromagnetic signal reflect off objects in the environment, taking paths of different lengths between hosts [4].

Electromagnetic radiation attenuates as it passes through these obstacles (walls, floors, foliage, etc.). Higher frequency signals such as the 5GHz frequency band have higher attenuation passing through obstacles than do lower frequency signals such as the 2.5GHz band as shown in figure 8. This is due to some of the energy of the electromagnetic field transferring into the material of the obstacle, which reduces the signal-to-noise ratio (SNR) of the received signal. Decreased signal strength with respect to distance traveled through an obstacle is an extremely important factor to consider when deploying a Wi-Fi network [7].

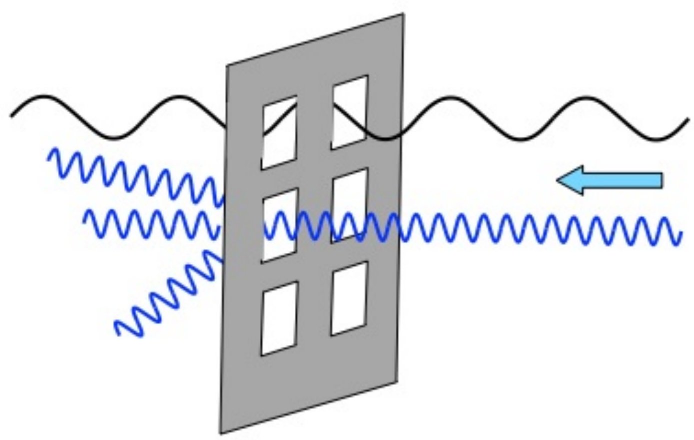

Figure 8. Dispersing frequencies copied from [7]

- Handover and Mobility:

Most Wi-Fi networks are not well organized, which in turn leads to erratic and insufficient system coverage and capacity. As deployed Wi-Fi networks are vulnerable to interference from other operating Wi-Fi signals transmitted by separate devices, it further affects the range, capacity and mobility performance of the network. Wide area networks (WANs) are not aware of the current radio characteristics of associated Wi-Fi access points, which in turn makes the handover between Wi-Fi access points more challenging [7].

Current solutions lack the ability to perform adequate handovers to Wi-Fi that satisfy mobility requirements for real-time services, making mobility an issue. Mobility is limited in most Wi-Fi networks as most devices search for a new access points only when the signal from the current associated access point becomes too weak and faint. Consequently, this makes Wi-Fi networks unstable as it leaves no guarantees, i.e. connectivity may not always be to the strongest access point, thereby limiting the networks' optimum efficiency [10].

2.2 Cellular networks

Cellular networks are wireless WANs that establish connections between mobile users. This is achieved through a radio network distributed over land areas called "cells". The term *cellular* refers to the fact that the region covered by the cellular network is partitioned into these geographic coverage cell areas with each cell being serviced by one or more fixed location radio transceivers. These radio transceivers are known as a Base Transceiver Stations (BTS), Base Stations (BS) or cell sites and operate mainly to transmit to and receive signals from mobile stations (MS) in its cell area. If a MS is within a cell area and is subscribed to that mobile operators cellular network, the MS will be able to pick up that cell signal [4].

2.2.1 Cellular architecture

A typical cellular network can be looked upon as a mesh of hexagonal cells, as shown in Figure 9 below, with a BTS at the center of each cell. Each cell is referred to as a *macrocell.* The BTS in the marcocell is connected to a Base Station Controller (BSC), which may be physically located with the BTS and primarily controls one or more BTS. The role of the BSC is to provide intelligence to the BTS through BTS handover management, allocation of radio channels, call setup and radio network management such as radio frequency control.

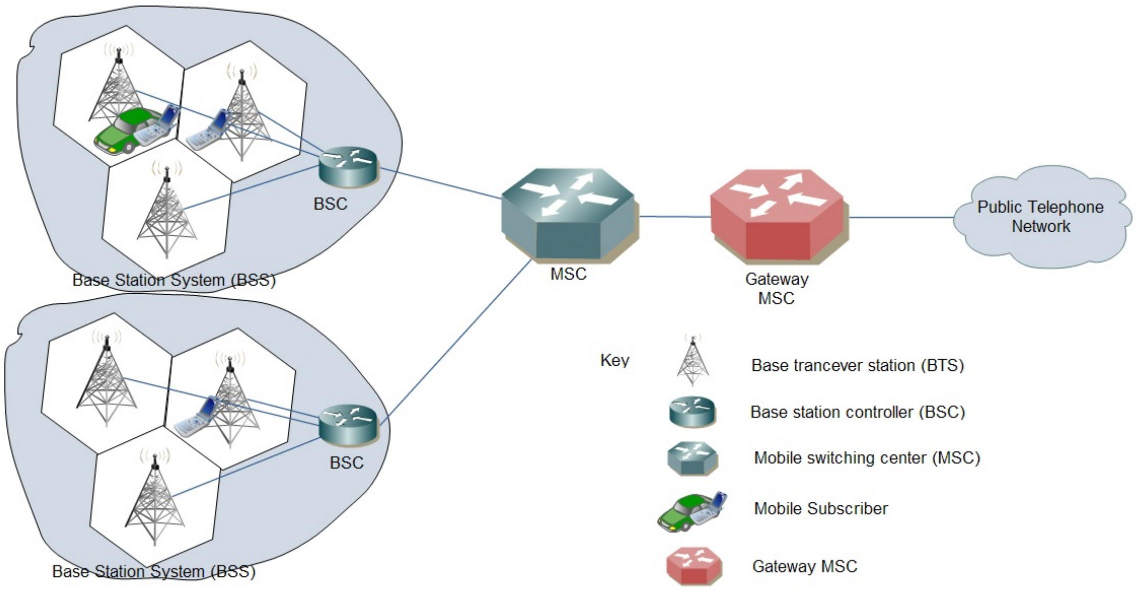

Figure 9. Components of a cellular network architecture copied from [4]

The BSC and an operating mesh of BTS's collectively make up the cellular Base Station System (BSS). The BSC communicates with the Mobile Switching Center (MSC) component, which is external to the BSS. The MSC provides the information that is required to support mobile service subscribers, such as authentication and user registration information. It connects calls by switching the digital voice data packets from one network path to another. This process is known as *routing* [4].

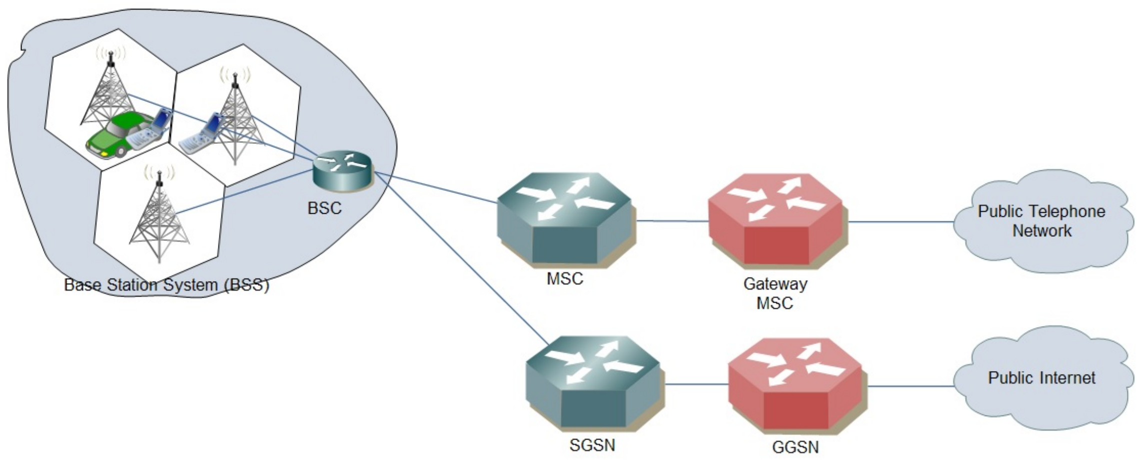

Figure 10. Cellular voice and data network architecture copied from [4]

The BSC serves as a mediator between BTSs and the MSCs while also eliminating MSC activity management requirements as shown in figure 10. This allows the MSC to handle critical tasks, such as database management and traffic balancing. The Gateway MSC (G-MSC) connects the entire network to the much larger public telephone network; in essence all connections in a cellular network are routed through the G-MSC.

In order to extend the cellular network to adopt not just voice but data services, the network has evolved to provide high-speed Internet access without altering the core of the cellular network. This is achieved by providing Internet access at the edge as a separate add-on functionality. This add-on functionality is implemented at the intelligence of the network, the BSC, and via the introduction a separate network of Serving GPRS Support Nodes (SGSN). At the BSC, information is forwarded to the SGSN, which communicates with the MSC to perform user authentication functions and then forwards the information to the Intermet [11].

2.2.2 cellular network technology evolution

Cellular technology like Wi-Fi technology belongs to one of several generations. Cellular networks can generally be grouped into four generations, namely 1G, 2G, 3G and 4G. Each generation is an improvement on the previous generation in terms of performance and cost. The latest step in the evolution process is the fourth generation (4G) Mobile

WiMAX Release 2 and LTE Advanced (LTE-A). In order to understand where cellular technology is at present, it is important to understand the evolution process and how the previous iterations shortcomings were overcome.

- First generation (1G):

First generation cellular systems were Frequency Division Multiple Access (FDMA)-based analogue telecommunication standards that were introduced in the 1980s and continued until replacement by 2G digital telecommunications in the following decade. The Federal Communications Commission (FCC) initially allocated a 40-MHz spectrum in the 800-MHz band for first generation cellular networks in 1983, and later in 1989 added an additional 10 MHz to accommodate the increasing demand for cellular communications. 1G networks operated with FDMA, this means each channel occupies a narrow band of 30 kHz. It transmits 3-kHz voice signal over the 30-kHz channel using frequency modulation [12].

The main motivation behind the 1G cellular network is that frequency reuse is possible. Frequency reuse is a technique of reusing frequencies and channels within a communications system to improve capacity and spectral efficiency. This meant that each cell had a frequency that was far enough away from the frequency in the bordering cell that it does not provide interference problems.

First generation (1G) mobile systems suffered from many disadvantages such as lack of security due to the lack of data encryption because of the analogue nature of the signals. In addition 1G network suffered from interference, transmissions could be picked up with an all-band radio receiver, and poor voice quality hence the need to replace them with 2G technology [13].

- Second generation (2G):

Second generation cellular networks were commercially launched on the Global System for Mobile Communications (GSM) standard in 1991. GSM was developed to operate in the 900-MHz band (GSM 900), and then was expanded to the 1800-MHz band (1710–1880 MHz), also known as the GSM 1800. The North America version of GSM is called the Personal Communications Service (PCS) 1900 because of its use of the 1900-MHz PCS spectrum. GSM uses the Time Division Multiple Access (TDMA) digital technology. This meant the allocated spectrum is divided into multiple channels of 200 kHz using Frequency Division Multiple Access (FDMA), and each 200kHz channel is dynamically shared by a number of users (up to eight) using TDMA.

The major advantage 2G networks possessed over their predecessors was that phone conversations were digitally encrypted. This meant that the new encryptions prevented eavesdropping. Primarily intended for voice services, 2G systems were significantly more efficient on the spectrum, facilitating far greater mobile phone penetration levels. 2G introduced data services for mobile, starting with fax and email services at low bit rates (8 to 9kbps) and then SMS text message services, all through circuit switching. The main difference between the 1G and 2G network was that while radio signals on 1G networks were analogue, radio signals on 2G networks are digital. The digital nature of the 2G network made error detection and correction possible, giving clearer voice reception previously not experienced in 1G networks [14].

Another feature GSM introduced was the Subscriber Identity Module (SIM) card. A SIM card is an integrated circuit that can be inserted into a cellular device to authenticate and identify subscriber information. 2G has been superseded by newer versions such as Code Division Multiplex Access (CDMA) based 2.5G and 2.75G; each user in CDMA is assigned a unique code to encrypt the data to be transmitted. Knowledge of the transmitters code enables the receiver recover and decipher the original message from the received data, making CDMA superior to FDMA and TDMA. Although new network technologies and standards have been developed (3G and 4G), 2G networks are still widely available and employed worldwide [14].

- Third generation (3G):

As 2G networks became widespread, the demand for access to data services and greater speed for these services became larger. In 1999, the International Telecommunications Union (ITU) selected CDMA as the industry standard for next generation of cellular systems. The third generation of cellular networks (3G) was developed to meet these high demands. The goal of a 3G cellular system is to provide all kinds of services: voice, high-speed data, audio and video. For a network to be recognized as third generation, it has to conform to a certain speed requirement (at least 200kbps) for information transfer and also be able to seamlessly transition from a 2G network [15]. The main technological difference that distinguishes 3G technology from 2G technology is the use of packet switching rather than circuit switching for data transmission.

3G has also been superseded by newer versions often denoted as 3.5G and 3.75G, however, 3G networks are still widespread and adopted worldwide. Cellular technologies specified by the Third Generation Partnership (3GPP) - a collaboration between groups of telecommunications associations, known as the Organizational Partners, are the most widely deployed in the world, with over 2.6billion users in 2008[16].
The scope of 3GPP is to make a globally applicable 3G-network specification based on evolved (GSM) specifications within the scope of the International Mobile Telecommunications-2000 (IMT-2000) project of the ITU. 3GPP developed the Universal Mobile Telecommunication System (UMTS) standards in 1999 within the IMT-2000 set of specifications for 3G networks. UMTS was based on wideband code division multiple access (W-CDMA) radio technology, offering larger spectral efficiency and bandwidth

than cellular network operators. The latest advancement in 3GPP cellular technology is the Long-Term Evolution (LTE) and an evolved packet access core network in the System Architecture Evolution (SAE) [15].

- Fourth generation (4G):

4G is the successor to 3G and 2G mobile communication technology standards. For a network to be recognized as 4G, it needs to conform to a set of requirements established by the International Telecommunications Union-Radio communications sector (ITU-R) known as the International Mobile Telecommunications Advanced (IMT-A) specification. Speed requirements for 4G services have been set by the ITU-R at 1Gbps for low mobility communications and 100Mbps for high mobility communications, making it 250 times faster than the 3G technology [17].

A 4G system is expected to provide a comprehensive and secure IP-based “anytime, anywhere” voice, data, and multimedia telephony at *faster* data rates than 3G based on mobile broadband solutions to mobile cellular devices. Applications such as ultra-broadband Internet access, IP telephony, video conferencing, cloud computing, and streamed multimedia will be offered to users [18].

Current technologies such as Mobile WiMax and Long Term Evolution (LTE) have been commercially deployed and branded by network providers as 4G. It has however been debated if these technologies should be considered to be 4G or not, as they do not conform to the specifications set by the ITU-R. The absence of a true 4G network does call into question, why network providers call their highest bandwidth 4G, as current technology does conform to the set standards. A mobile station (MS) picking up a 4G signal is really just picking up a modified 3G signal [20].

Newer versions of these so called 4G technologies are to be launched late 2013- the Mobile WiMAX Release 2 (also known as *WirelessMAN-Advanced* or *IEEE 802.16m'*) and the LTE Advanced (LTE-A) are said to be IMT-Advanced compliant and backwards compatible versions of their predecessors, and promise speeds of up to 1Gbps [20]. Figure 11 depicts the cellular network evolutionary stages and the technology used in each evolution.

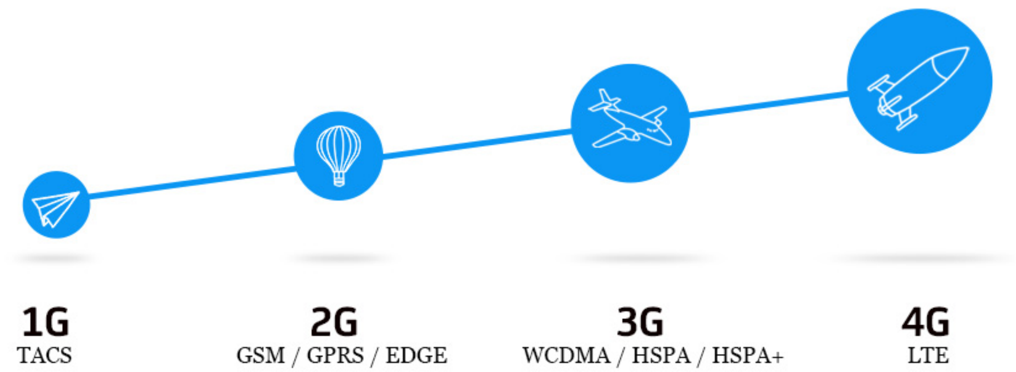

Figure 11. Cellular network evolution copied from [21]

2.2.3 Introduction to Femtocells

With the proliferation of smart devices and the overabundance of connected devices, wireless service operators face increasing demand for mobile broadband services. As cellular technology evolves, now entering the 4G era, the introduction of small cell technology promises to enhance services and system capacity by facilitating improved coverage that suits ever growing end-user requirements for indoor communications.

Recent studies have shown that due to the strenuous demands on the available bandwidth, alongside the ever increasing rate at which data traffic is growing and the poor QoE faced with indoor communications [22], in order for cellular networks to remain relevant in areas pertaining to voice and data services, cellular service providers have to reform their marketing and service delivery strategies together with their overall network architecture. To accomplish this leap forward in performance cellular service operators need to employ a network topology evolution, which makes use of a mix of macrocells and small cells, effectively bringing the network closer to the end-user.

It has become increasingly important for cellular service providers to employ small cell technology that will facilitate coverage that suits end-user's growing requirements for both indoor and outdoor communications. These small cells are also known as home base stations. They communicate in a licensed spectrum which offers improved indoor coverage with an increased performance. These small cells function with the operator's approval; offering improved voice and broadband services in a low-cost technology agnostic form. For these small cells to function, they must be placed within the macrocell hexagonal grid in order to obtain the cellular provider's coverage [22].

Availability of spectrum has become a major concern in supporting mobile broadband growth as attaining efficient signal strength in an indoor environment triggers a major challenge for cellular service providers. This is due to cellular electromagnetic radio waves being obstructed by floors, walls and other structures thus facing the effects of attenuation and multipath fading [23]. Subsequently, the Received Signal Strength (RSS) at an indoor site will be reduced. The inevitable convergence of cellular and Wi-Fi technologies and services could be considered the evolution of both the technological and marketing sides of wireless communications, with the result being a *Femtocell.*

As mentioned earlier, attenuation of electromagnetic signals are more prominent at higher frequency bands such as the ones used in cellular networks [4]. Cellular networks use a portion of the radio frequency spectrum known as Ultra High Frequency (UHF), which is used for higher bit rate operations such as satellite communications and broadcasting [23]. With neighboring cells employing frequency reuse by using a different set of UHFs to avoid interference, the ITU-R recommends cellular networks use frequency bands within the ranges of 806–960 MHz, 1710–2025 MHz, 2110–2200 MHz and 2500–2690 MHz. Besides the 806 MHz frequency, these UHFs are more susceptible

to attenuation than the ISM frequency bands used by 802.11 WLAN networks thus making indoor cellular communications not as effective as possible [24].
Small cell technologies such as Femtocells, Picocells and Microcells are the proposed solution for this reduced RSS. These technologies support compatibility with the cellular systems while providing better indoor signal strength that is usually unattainable by macrocells operating at higher UHFs. Small cells are designed to be compliant with the standards supporting the operator's mobile technology of choice, this means all small cell technology standards are part of the existing plans and roadmap for all the major families of mobile technology, including 3GPP, 3GPP2 and WiMAX [26].

A Femtocell, as shown in figure 12, provide better indoor signal strength through the use of an IP network as the backhaul infrastructure instead of the conventional cellular network infrastructure. In other words, Femtocells allow cellular service providers to extend service coverage indoors or at the cell edge, particularly where access would usually be limited or unavailable. This is made possible by employing a Femtocell Access Point (FAP), also known as a Femtocell base station, placed in an indoor environment (residential or enterprise) that has broadband Internet connection. The Femtocell connects locally to standard cellular devices through normal airlink protocols like GSM, CDMA, and UMTS connections, and then routes the connection to the operators backbone network through the FAP and the Internet, with the Internet being the intervening network, using the available Internet connectivity provided by Internet Service Provider (ISP), bypassing the macrocell network. This connection is end-to-end i.e. it is identical to the one which would directly connect a mobile devices to the cellular network through outdoor macrocell BS [25].

The motivation behind the deployment of small cells solutions such as the Femtocell is due to the current mobile networks being overloaded and the poor quality of Received Signal Strength (RSS) in indoor locations. Recent Cisco studies show that the vast majority of data traffic originates indoors; cellular network subscribers use mobile data services 40% of the time from home, 25% from work, and 35% from public locations. With at least 80% of the traffic coming from indoor locations where conventional macrocell coverage yields weakened RSS due to electromagnetic attenuation [22], indoor data traffic could be routed into the cellular network using a nearby Femtocell base station, leaving the corresponding user to experience an increase in voice and data service capacity while in addition, sparing the macrocell base station resources, which in turn implies a reduction in network maintenance and deployment costs for the cellular network operator.

Figure 12. Femtocell Access Point (FAP)

Femtocells, either currently being used under 3G specifications or as future LTE/4G epitomes have attracted huge interest from both mobile operators looking for new areas of commercial revenue in lieu of the reducing satisfaction and unappealing Quality of Experience (QoE) traditional cellular networks provide, and from end-users eager to significantly upgrade voice and data communications made indoors with the added Quality of Service (QoS) guaranteed by networks operating in a licensed spectrum.

2.2.4 Femtocell architecture

The Femtocell access point (FAP) is as a small cell site with a relatively small footprint (about the size of an average WAP) for indoor areas. In order to operate, the FAP must be connected to a broadband Internet connection via residential DSL, cable broadband connections, optical fibers or wireless last-mile technologies. A typical FAP transmits at 100 mW or less, which is significantly less in comparison to the outside macrocell (about a thousand times weaker) and about one-fifth the transmit power level of a typical WAP. Transmit power levels of FAPs are this low because Femtocells are designed to cover a few meters. It is crucial that the Femtocells have this limited coverage range in order to avoid unwanted interference with the macrocell networks which use the same radio spectrum. Once installed, the Femtocell is transparent to the cellular user; i.e. the Femtocell appears to the cellular device as just another cell site from the cellular network provider.

Range is limited to about 30 meters, depending on the height of the FAP and the local clutter (obstacles) in the environment. When a *registered device* enters the range of a FAP, handover to the Femtocell network is done automatically, such that connections are channeled through the broadband connection. Unlike Wi-Fi, Femtocells require no special hardware or software support on the mobile devices they connect to. Emphasis is made on the *"registered devices"* as subscribers must register the identities e.g. cellular numbers of the devices that are authorized to access the FAP [27].

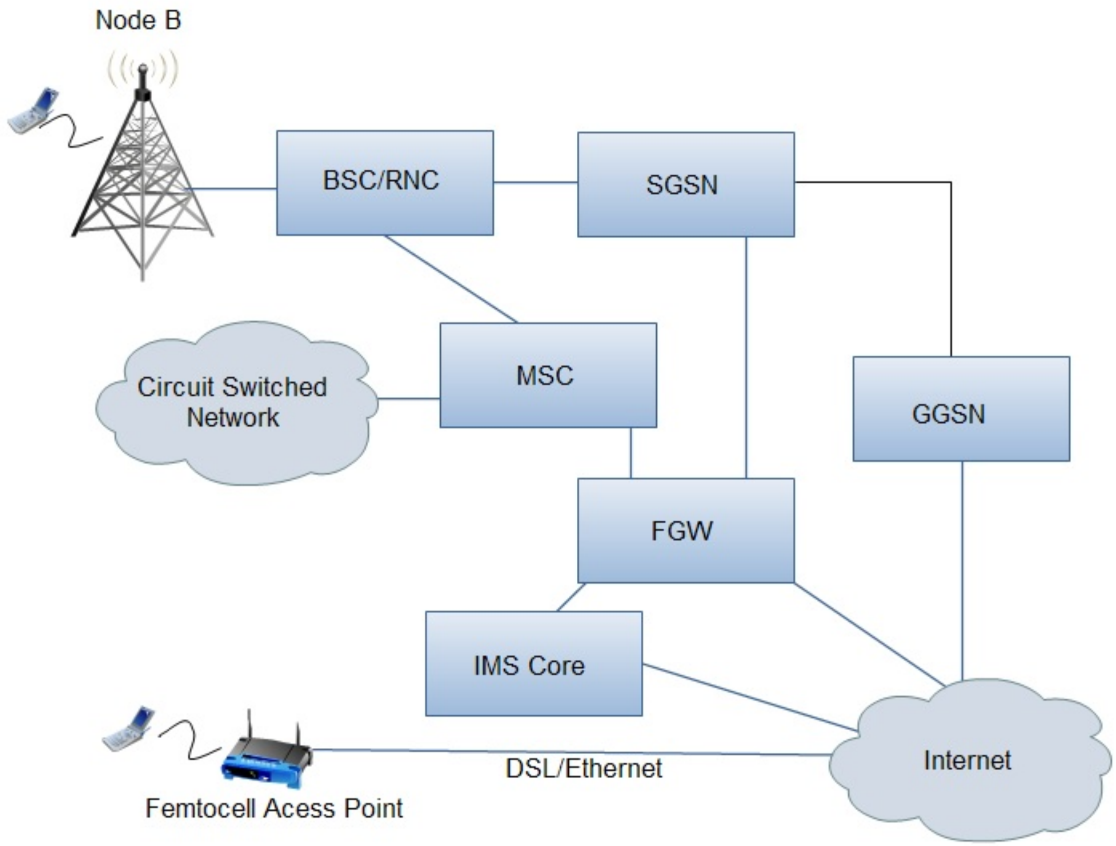

Figure 13. Overview of femtocell network architecture copied from [23]

Femtocells allow conventional cellular devices use the resources of both cellular and IP networks. This is possible because the Femtocell controller provides the interface between IP and cellular networks. As shown in figure 13, the FAP is interfaced to the local termination of the broadband Internet connection (e.g., cable modem or DSL, typically via Ethernet) and through the Internet, each Base Station is connected to the Femtocell Gateway (FGW). The Femtocell Gateway as show in figure 14, provides interfaces to the conventional backbone network of the Mobile Operator equivalent to those used by macrocell networks; thus from the overall perspective of the Mobile Operator, Femtocells in conjunction with macrocells become seamlessly integrated with the overall functions and service offerings.

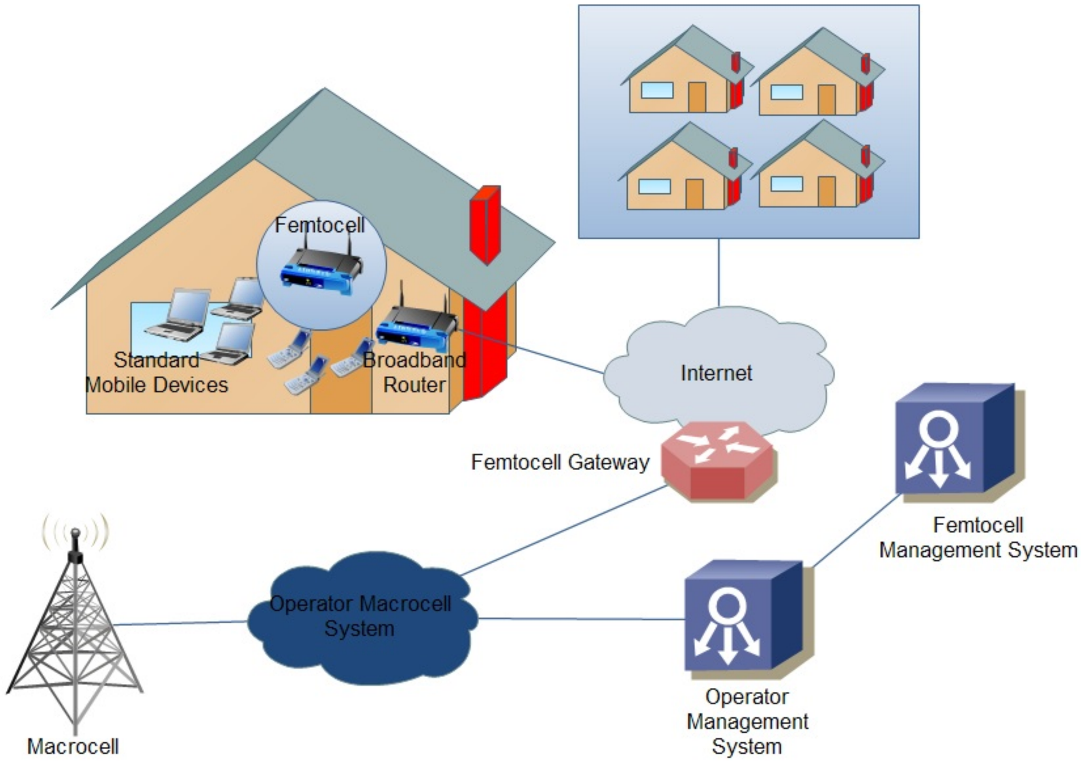

Figure 14. Femtocell deployment scenario copied from [25]

This means, the MSC and SGSN communicate to the Femtocell gateway in the same way for other mobile calls. Thus, all cellular services such as call diversion, voicemail etc. all operate the same way and appear the same to the end user operating the mobile device [23].

These overall functions and services include the provision of a suitable Operator Management System for operational functions such as software updates and diagnostic analysis, of which the Femtocell Management System comes into play.
Additional functionality for Femtocells include various specifications which may vary depending on the wireless protocol being used (GSM, CDMA, UMTS, CDMA2000, WiMAX, EV-DO or LTE), but all of them have three main elements:

- Self-organizing base stations (Femtocell Access Points): The Femtocell Access Point is the primary node in a Femtocell network that resides in a small office/Home office (SOHO). The FAP implements the functions of the base station and base station controller and connects to the operator network over a secure tunnel via the Internet. Unlike large macrocell BS, which require complex radio resource functions; smaller Femtocells configure and optimize themselves, operating nearly autonomously [35].

- Femtocell security gateway (FSeGW): The security gateway is a network node that secures the Internet connection between Femtocell users and the mobile operator core network which provides encryption support for all signaling and user traffic. The security gateway supports a large number of Femtocells connecting to the operator's network. The connection between the Femtocell and the operator network uses this gateway, which uses standard Internet security protocols such as IP encryption (IPsec) that avoids interception and authenticates the Femtocell itself to ensure it is a valid access point. Femtocell security gateways are designed for use in carrier networks and as such meet carrier-grade requirements i.e., high availability, sufficient scalability and network management.

- Femtocell Network management system (FMS): The Femtocell management system (situated in the operator network) plays a major role in the activation, provisioning and operational management of Femtocells using industry standards such as TR-069. This system allows the network operator to make software updates and run diagnostics thus performing end-to-end management and supervision functions similar to those implemented in the macrocell networks. This management system is arguably the most important part of the Femtocell architecture as it must comply to TR-069 protocol which is a protocol for communication between Customer Premise Equipment (CPE) and Auto-

Configuration Servers (ACS) that encompasses secure auto configuration as well as other CPE management functions within a common framework ensuring the scalability of a Femtocell network to a large number of devices. Various standards bodies specify the use of the TR-069 family of standards as the base device management framework for Femtocells. This protocol is extensively used in DSL modem and residential gateways, and uses a web-based architecture that can support large number of end user devices [28].

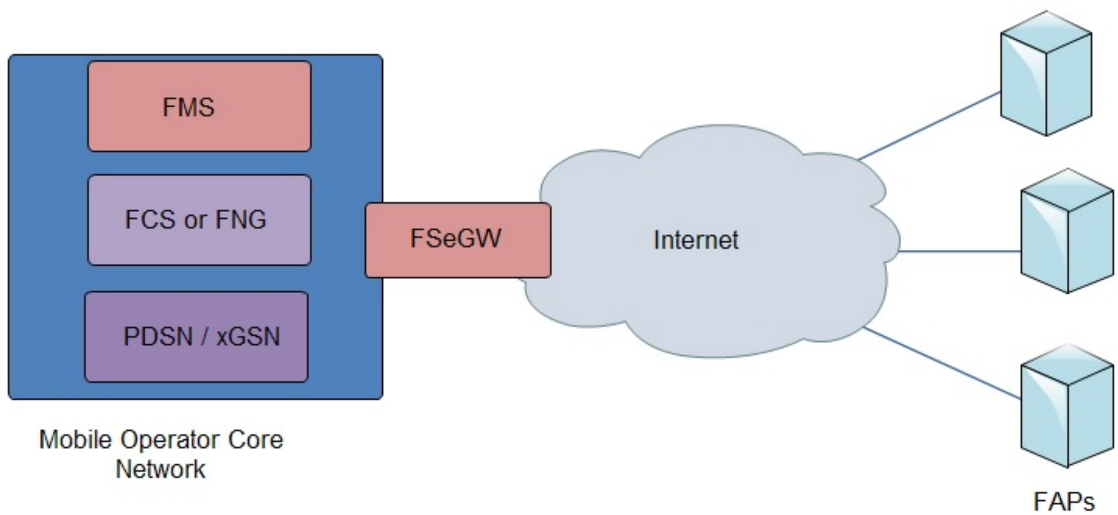

Figure 15. Common elements of the Femtocell network architecture copied from [28]

Two other elements that are in all Femtocell network architectures are entities that enable connectivity to the mobile operator core. Depending on the particular architecture deployed for circuit switched calls, there may either be a Femtocell Convergence Server (FCS) or a Femtocell Network Gateway (FNG) as shown in Figure 15. For packet calls, depending on the wireless technology, there can be either a Packet Data Serving Node (PDSN) or Gateway / Serving GPRS Support Node (GGSN/SGSN) in the core [28].

- The FCS or FNG: this enables Femtocells to connect to the operator core network. This is crucial for Femtocells to operate, as this is what allows Femtocells to communicate with the core elements in the operator's networks and allow seamless service for the mobile. For instance, basic call setup requires communicating with the MSC and PSTN of the operator core. The FCS or FNG makes this possible.

- The PDSN / xGSN: this enables Femtocell users to receive packet data services over the mobile operator's core. These packet data services are the same as those used by the mobile operator's macro network.

2.2.5 Femtocell Issues and Technical Considerations

Although early reports forecast that the global small cell market will grow rapidly, the actual market interest in small cells is not as large as predicated [54]. Like any new technology, Femtocells come with issues that need to be resolved for them to become a successful, widely deployed technology. Femtocells need to be scalable and integratable. They also must be tough enough to handle signal interference and support synchronization. Lastly, Femtocells must adhere to all regulatory requirements.

- Frequency and Bandwidth:

As mentioned earlier, Femtocells operate on the same licensed spectrum that is allocated to the macrocells of cellular service providers making the electromagnetic spectrum a crowded resource. To deal with this issue of overcrowding, two methods have been deployed, the Co-channel Frequency Deployment and Orthogonal Channel Deployment.

The Co-channel Frequency Deployment allows the Femtocell and the macrocell to use the same frequency band. With this co-channel method, interference issues arise (which will be discussed later in this section). The other method, Orthogonal Channel Deployment could be considered the opposite of Co-channel Frequency Deployment. In this method macrocells and Femtocells use separate channels. The advantage of this method is that there is less potential for interference, and on the other hand, the disadvantage is a reduction in the overall system performance due to additional overhead the system has to employ [54].

- Interference:

One of the concerns faced by operators is the potential for harmful interference to the macrocell network due to both the Femtocell and the macrocells operating on the same licensed spectrum. This is known as femto-to-macro interference or a cross-layer interference. When several Femtocells are serviced by the same macrocell base station (BS) there can be adjacent channel interference. Interference issues also arise from FAPs in close proximity to each other regardless of which macrocell it's connected to. This is known as femto-to-femto interference or a co-layer interference. Due to the low transmit power FAPs need to operate, these close proximity FAPs causing interference with each other would have to be extremely close to cause this interference, so its very unlikely this would be a major concern.

Interference issues have been reduced due to the Femtocell interference management techniques as per the 3GPP (release 7) standard [32]. This technique involves using self-organizing methods to detect nearby macrocells signals, and on the downlink; Femtocell carrier selection and transmit power self-calibration. On the uplink, adaptive attenuation techniques are used at the Femtocel, limiting the transmit power thus reducing interference [33].

- Regulations and licensing:

Femtocells operate under a licensed frequency spectrum; this is very unlike Wi-Fi networks that do not require any regulatory approval to operate. In a licensed spectrum, the provider subscribes to be allowed to use a portion of the spectrum exclusively and regulators will enforce transgressions. These regulators ensure that operation within the licensed spectrum is of a specific standard, enabling better QoE for the end user.

Due to spectrum and radio frequency regulations varying from region to region, it becomes an issue to Femtocell operators that move from one region to another. Due to the regulatory issues, operators cannot use Femtocells in frequency spectrums that have not been subscribed for. The varying spectrum allocations from one country to another will also prevent unauthorized usage of Femtocells in regions with different regulatory rules [38].

Another regulatory issue not to be overlooked is the relationship between the Femtocell operator and the broadband service operator. There are two possible scenarios, first is that the broadband operator may be unaware of the presence of a Femtocell operator. Secondly, the Femtocell operator and the broadband service operator may be under the same service provider. In the second case, there might arise regulatory concerns due to possible unfair pricing or agreements made between the service provider and the Femtocell operator or broadband service operator [30].

- Quality of service (QoS):

QoS refers to the ability of a network to provide certain requirements to different applications and forcing different priorities for these applications, guaranteeing a specific level of performance for data flow. The motivation behind standardizing QoS in wireless equipment is to guarantee an adequate level of quality and performance during operation for the end-users data traffic needs. Some of these requirements include, sufficient SNR, frequency responses, loudness levels, response time, loss, etc.

Wi-Fi networks already comply with the four IEEE 802.11 QoS standards (Best Effort, Video, Voice, and Background) and have established mechanisms employed to ensure QoS [26]. Femtocells on the other hand support QoS as an integrated part of Macrocell network. Coordination between macrocell and Femtocells facilitates smooth and transparent flow of QoS sensitive traffic flows. Although, Femtocells may require several upgrades in order to achieve adequate QoS requirements to end-users. Advanced traffic classifying techniques such as Differentiated Services (DiffServ) and Integrated Services (IntServ) may have to be deployed in order to reach a desired QoS level. IntServ improves QoS by having applications use resource reservation protocol (RSVP) to improve requests and reserve resources through a network, while DiffServ prioritize packets according to the type of desired service [40].

Once these upgrades are in play, service providers may choose to deploy a simple QoS class-based model, which provides operators with an efficient way to differentiate between services while supporting subscribers with variable levels of service quality. This provides operators the opportunity to support differentiated type of services with the potential for offering innovative billing and pricing models with the Femtocell. For example, the network can prioritize certain types of packet with QoS for immediate and secured delivery, improving subscriber experience and service delivery.

Although QoS is ensured by these upgrades and the operation of licensed spectrum regulations, Femtocells access the global IP through multiple steps in the mobile operator’s domain, and for each single interaction; it becomes more complex and time consuming, which affects the overall performance of the network [39].

- Handover:

As mentioned earlier, handover occurs when devices in wireless networks move from one access point to another when the RSS of the former becomes lower than a certain threshold. Due to the small coverage area Femtocells possess, seamless handover from one access point to the next is essential in order to maintain continuous signal connectivity. There are three types of handovers for wireless connectivity, first being a normal handover. This occurs when the device is moved from the range of one base station to another base station (BS-BS handover). The second occurs between base stations and Femtocell Access Points (FAPs). This occurs when a device moves from a BS range into a FAP range of transmission, or vice versa (BS-FAP handover). For this type of handover to be possible, there needs to be synchronization between the FAP and the BS because there is no central co-ordination between the two. The third type of handover occurs when the device is moved from one FAP range to another FAP (FAP-FAP handover). This occurs when there are several FAPs operating within proximity [41].

All handovers must be done seamlessly in order to maintain connectivity to the network. For these handover cases, appropriate neighbor cell list is the key element for the successful handover. Large and dense scale deployment of Femtocells within a small coverage area may result in interference effects and handover issues may arise due to inaccurate neighbor cell lists. A hidden FAP may cause an inaccurate list. This problem occurs when a neighbor FAP is very near to the BS but the BS cannot receive the signal due to some barrier (e.g., wall) between the BS and that FAP. Thus, the hidden FAPs will be out of neighbor Femtocell list. These neighbor lists are created by the BS based on received FAP signals, hence, two major challenges arise; inclusion of some unnecessary Femtocells in the neighbor Femtocell list and exclusion of some important hidden FAPs from the neighbor Femtocell list. For densely populated Femtocell areas, an intelligent integrated Femtocell/macrocell network architecture, a neighbor cell list with the lowest number of Femtocells, an effective call admission control (CAC) and a handover processes with proper signaling are necessary when deploying Femtocells [55].

- Security:

Security concerns for any wireless network is very important. It is a major concern to operators who see Femtocell deployment as an integral part of their roll out of new technologies such as LTE. Security concerns such as user privacy, denial of service, general service availability and other fraudulent services are all major issues as Femtocells are vulnerable to attack. It can be assumed that the cellular core network is safe from these attacks as the core network is under the control of the cellular operator, and any security concerns would be maintained regardless of the operating state [4].

The first vulnerable area is the wireless link to the Femtocell. It is possible for external wireless transmissions to potentially gain unauthorized access to the Femtocell. The second vulnerable area is the Internet link; this backhaul link is used between the Femtocell and the gateway into the service provider's core network. The third vulnerable area is the Femtocell itself, it is possible for unwanted network users to gain access into the Femtocell and take control of it remotely.

In order to prevent Femtocell security attacks from succeeding, there are precautions that should be adhered. First, ensure encryption authentication as it is required by the service provider and the operator to correctly identify valid Femtocells within the network. The Femtocell and the network authenticate mutually and securely, so that the Femtocell becomes a secured part of the operator's network and is fully controlled by the operator. The Femtocell resists meddling by a variety of physical and electronic techniques so that the user cannot change the Femtocell configuration and cause harmful or illegal interference - or indeed degrade the service that the user is paying for access via the Femtocell [43].

Next precaution is the use of IPsec. The IPsec standard is a widely used standard defined by the Internet Engineering Task Force (IETF) for securing IP communications by authenticating and encrypting each IP packet. It will ensure that the Femtocell security is maintained across the Internet [28]. Another precaution that could be taken is the use of extendable authentication protocol (EAP); it is an authentication framework for wireless networks that provide a means of ensuring wireless security. Finally, by employing wireless link security techniques to ensure that unauthorized users do not connect remotely to the Femtocell. This could be done by ensuring the Femtocell coverage area, does not exceed the physical parameters of the environment it's being used.

2.3 Key aspect comparison of Wi-Fi and Femtocell technology

When considering mobile communications, cellular technology and mobile service providers are currently leading the market place with the roll out of 4G/LTE technology. This is mainly due to key aspects of cellular networks such as the ubiquitous coverage from a single service provider, QoS levels in licensed spectrums and the seamless but sophisticated handover from one base station to the next. Wi-Fi networks, although having robust features cannot currently compete with these cellular network key features [47].

Unlike Wi-Fi, cellular service providers are uniquely positioned to provide services both in public and residential environments due to the vast coverage. This come as a major advantage because devices which use cellular 3G access to the Internet have an "always on" configuration, which means they are always connected to the Internet without the need of additional configuration, authentication or extra cost to the user. Extending these key features to mobile users located indoors where data demands are larger is what makes Femtocells so relevant. Upon reviewing both technologies in previous sections, a side-by-side comparison of key aspects of both Femtocells and Wi-Fi would give a clearer insight, as shown in table 2.

Key aspect	Femtocells	Wi-Fi
Spectrum availability	• Licensed band • Must re-use operator's available spectrum allocation. Thus mainly used for coverage extension as well as capacity improvement	• Unlicensed band • Operator need not bother with spectrum related issues as with Femtocells
Indoor coverage	• Up to 10 – 30m with transmit power of 1mW to 100mW • Power level will depend on the macrocellular network to avoid/mitigate interference	• Up to 100m with transmit power of up to 1W • Power levels are usually higher than Femtocells
Interference issues	• Co-channel interference with macrocell • Interference avoidance and management methods utilized	• There are interference collation features utilized, although interference from non Wi-Fi unlicensed band devices can be an issues if gone unchecked
Data offloading	• Data off loading is inherently supported, making it possible to have a uniform data plan throughout the network	• Data offloading is not inherently supported.
Handoff support	• Uses the same technology as macrocells making it easy for a hierarchical handoff	• Needs a user triggered mechanism. No seamless handoff
Quality of service (QoS)	• As the licensed band is managed by the operator, QoS is carefully managed	• QoS issues may arise as operator may not have control over Wi-Fi network
Device support	• No special considerations on the device	• Device needs to have Wi-Fi compatibility
Total cost of ownership	• Deployed by the operator and is paid for by the end-user	• Possibility of partnering with third parties for Wi-Fi access

Table 2. Key aspect of technologies [27]

2.4 Femtocells in South Africa

Recent Cisco Visual Networking Index (VNI) forecast have predicted that the South African Internet protocol (IP) traffic is set to quadruple over the next five years (2012-2017) at a compound annual growth rate of 31%, putting strain on the expensive wireless spectrum.
South Africa's IP traffic (fixed and mobile) is expected to reach an annual run rate of 6,1 Exabyte's (almost 6,55-billion gigabytes per year) by 2017 [22].

According to Cisco Consulting Services (CSS), these staggering projections threaten to overload the capacity of regional mobile operators, who may be struggling to ensure availability of high-speed packet access (HSPA) and LTE spectrum.
Mobile data offload solutions such as small cell sites are just one of the business model solutions the CSS recommend South African operators adopt to achieve maximum results with limited spectrum.
CCS studies emphasize that mobile data offload will enable mobile operators to maximize the benefits of alternative technology such as Wi-Fi and small cells. Theses solutions offer operators revenue assurance, generation and better-quality services. This prescribed business model is a viable alternative for serving mobile broadband users in crowded public locations such as malls, where the availability of spectrum for HSPA and LTE mobile access networks is limited. Furthermore, mobile data offload will give service providers the opportunity to lessen data costs, allowing them to fast-track adoption and increase market share [22].

Though this business model of offloading data onto Wi-Fi or small cell sites looks promising for South African cellular providers, Cisco cautions that adopting this model requires significant investment. Cisco Consulting Services determined that South African mobile operators would have to invest $108 million (20% would be allocated to CAPEX and 80% to OPEX) between 2013 and 2017 to provide just Wi-Fi coverage to 564 buildings with total indoor space of 2,4 square kilometers and total outdoor space of

25,5 square kilometers for busy locations across Johannesburg, Germiston, Pretoria, Durban, Port Elizabeth, East London, cape town and Bloemfontein [22].

Although having cellular service providers roll out Wi-Fi technology as a mobile data offload solution would generate significant cost savings in the long run (offloading 30% of the overall traffic will enable mobile operators to reduce costs by 27% and obtain savings of up to $972-million in five years), it is still not yet adopted and neither is the small cell site solution even though service providers have the equipment and are set to roll out [45].

2.4.1 Limitations in South Africa

Although the uptake of Femtocells has not been as large as predicted by the most optimistic early market studies [31], deploying small cells solutions such as Femtocells is a major challenge for South African cellular providers. As is with most new telecommunications technology, deployment raises questions as to the way the new technology fits with existing regulations, as there is a lot of regulatory, financial, health and safety and economic issues hindering the roll out. Limitations include but are not limited to:

-Economic and Regulatory issues:

The independent communications regulatory authority (ICASA) in South Africa is yet to adopt policies that cater towards the Femtocell deployment. The low levels of radio waves emitted by a Femtocell and the low transmit power usage (less than 0.1 watts) by the FAP has not yet been approved by ICASA for use in residential environments. The stand-alone device is still looked upon by the regulatory authority as a macrocell and is thus treated as one. This brings up a number of challenges as a substantial sum is charged to the service providers for the operation of each base station. While this charge may be acceptable for high-powered conventional macro BS, such requirements are excessive and redundant for low powered Femtocells and will thoroughly undermine the benefits of Femtocells for consumers and the operators [37].

- Operator Liability:

These ICASA regulatory limitations also stipulate that the service provider must take on full responsibility for each Femtocell being deployed in a SOHO environment, even though the infrastructure (access point) is owned by the end-user. This is a major challenge, as service providers by law require qualified personnel to install each Femtocell access points in every home or office or have a third party install the access points under the operators direction (even though Femtocells can be installed by the end-user) along side a legible health and safety warning label and must take full liability for any injuries or health factors caused by the emissions from the Femtocell access point [37].

- Consistent Documentation:

ICASA regulations also require operators to supply records of base station locations. While operators like to know the locations of their base stations for their own service and network management motives, the need to tender records of every FAP deployed in South Africa creates an excessive burden on operators and ICASA regulators alike. Such a tedious requirement would also be inconsistent and unreliable given that FAPs may be moved from one location to another depending on the end users needs. This is also a major disadvantage to Femtocell vendors as such records are not required for low power systems such Wi-FI access points [37].

These regulatory drawbacks are very unappealing to service providers as it proves uneconomical for the operator to submit detailed records for every deployed Femtocell and the financial implications of deploying a small cell with the possibility of being liable for health and safety of the end user, even though Femtocells fully comply with the guidelines for human exposure to electromagnetic emissions issued by the International Commission on Non-Ionising Radiation Protection (ICNIRP).

- Architectural Challenges:

Besides the regulatory drawbacks, there are also the architectural challenges faced by the service providers, as operators need to find the right combination of coverage. Wi-Fi can provide hotspot coverage, but does not have the advantages of operating in a licensed spectrum, and seeing as small cells can only have a single operator, these Femtocells must be placed in temporary areas within the enterprise's network architecture in case the organization chooses to reshuffle its access points or change operators entirely [37].

ICASA has currently involved Cisco in field trials and talks with the *femto forum* – a non profit organization devoted to promoting Femtocell technology worldwide, to come up with regulations that cater to the wide spread deployment of Femtocells in South Africa. The Femto Forum's members have considered these concerns and in general believe that very few changes, if any, to regulations are required. Telecommunication regulators are supposed to provide clear guidance as to what new telecom technologies can bring to a country. With the telecommunications industry constantly changing and bringing up new innovations, these regulatory authorities too must change and evolve to cater to these technologies so as end-users may benefit. South Africa could learn from other countries (like the UK, US, Japan, China, France, Portugal and Singapore) that have adjusted telecommunication regulations to allow the commercial deployment of Femtocells. Such adjustments inevitably lead to a cost effective means of improving consumer access to mobile services, reuse of existing mobile operator spectrum for Femtocell operation thus improving spectrum efficiency, and the reduction of the deployment and operating cost of mobile broadband services thus increasing value of services for both the end-user and the service provider.

If new regulations could be established that allow the operators to deploy Femtocells, there will be a number of benefits for the South African telecoms industry and the South African telecoms consumer base [37].

2.5 Conclusion

This chapter serves as an introduction to wireless network communications, establishing operational principle and the architecture of both cellular and Wi-Fi technology along with the technical issues and considerations that must be observed when choosing one technology over the other. This chapter further reviews the evolution of cellular network technologies and ends with a summary of how the investigation is organised.

3. Problem Statement

3.1 Introduction

In this chapter, the key research topic is further clarified. As operators evaluate how to invest in the next generation of wireless broadband technologies, it is imperative for these operators to get a genuine outlook at the true capabilities and technical differences of the technology choices available to them in order to make choices that will meet the long-term demands of the future. These technical differences are shown in table 3.

Operators facing capacity challenges in a limited spectrum environment can follow the conventional route of macrocell splitting by inserting more macrocells to their existing networks, however, this solution can be challenging and economically unappealing. Conventional macrocell sites require loads of equipment to be installed on rooftops or steel towers. These sites come at high cost and require expensive broadband connections and backup power, extensive drawn out site leases, and round the clock maintenance. Apart from the considerably large CAPEX and OPEX challenges faced by the cellular operator, providing adequate indoor signal strength has also been an area of concern. This inadequate signal strength is due to radio waves being obstructed by environmental obstacles resulting in lowered received signal strength (RSS) within the building [53].

3.1.2 Review of the Problem

For cellular service providers that need to significantly increase indoor network capacity, there are two complementary solutions for offloading macrocell user traffic, one being the deploying a network topology that employs small cells in the *same* channel as macrocells and the other being the deploying 802.11n Wi-Fi access points in unlicensed spectrum.

To compensate for this low RSS issue, the second solution recommends that operators deploy low power cells such as Femtocells which deliver more capacity and better range in an inherently noisy environment full of obstacles [10].
Femtocells could be considered as the convergence of the current cellular network technology with that of WLAN technology. They are more appealing to operators due to the small cell site footprint they require, ease of deployment, and low equipment and operating costs. This convergence of technologies requires the cellular device to connect to an IP backhaul instead of the conventional cellular infrastructure. As can be observed in the previous chapter, this makes the Femtocell and Wi-Fi infrastructure networks rather similar and thus raises various questions that this research endeavors to answer.

Considering the second solution – Wi-Fi, appears to be the preferred industry solution being used to offload traffic as it is becoming ubiquitous in new communications devices. In order to complement a managed Wide Area Network (WAN), Wi-Fi network operators can overlay Wi-Fi networks in unlicensed spectrum due to the over abundance of communication devices having built-in Wi-Fi access. This makes it possible for mobile operators to offload data from macrocell networks to Wi-Fi networks at residence and enterprise environments [10]. Wi-Fi being the already well-established technology, it is arguable that Wi-Fi users will not be easily sold on this Femtocell technology being the best solution for SOHO connectivity, asking – "Why would anyone be interested in acquiring a new access point to emit in a licensed spectral band, while existing Wi-Fi perform similar services at no extra cost?"

Although operators may decide to use a combination of both Femtocells and Wi-Fi technologies to offload traffic as it seems both solutions can address these network capacity issues independently; there are important differences in performance with the usage of Femtocells and Wi-Fi access points that this investigation aims to highlight through theoretical considerations and extensive experimentation.

The key research question for this proposed thesis is as follows:

- "Do we need Femtocells when there is Wi-Fi technology?"

3.1.3 Objective of the Investigation

The purpose of this investigation is to create a better understanding of these technologies through an analysis of the performance of the most common classes of current applications alongside the technical capabilities of each technology under various boundary conditions.
Using Femtocell access points (FAP) and Wi-Fi access point (WAP), controlled tests will be conducted in varying environmental conditions to ascertain which applications best suits Femtocells intrinsic characteristics, while conversely determining what the tradeoffs or penalties would be implied when compared to Wi-Fi technology, thus determining which technology is the better means of establishing wireless communications in an active residential or enterprise environment.

This investigation also aims to answer the following sub-questions by comparing various key network performance indicators and technical capabilities of both technologies:

1. Should Femtocell technology replace the current Wi-Fi technology?
2. What is the relevance of small cells in today's industry?
3. With both technologies able to provide convergent communication services (voice and data)?
4. Which technology is better for the mobile end-user? and
5. What are the implications on the mobile operator for rolling out Femtocells?

3.1.4 Technical differences between Wi-Fi and Femtocells

	Femtocells	Wi-Fi
Frequency Band	• 2.1 GHz – WCDMA/HSPA • 700MHz, 800 MHz, 1.8 GHz, 2.6 Ghz… -LTE/LTE-Advanced • 2.3GHz – mobile Wimax (WiBro)/LTE	• 2.4 GHz – IEEE 802.11 b/g/n • 5GHz – IEEE 802.11 a/n/ac
System Bandwidth	• 3G – 5 MHz per carrier • 4G – Up to 22 MHz per carrier	• 5 MHz, 10 MHz, 20 MHz • 40 MHz (IEEE 802.11n) • 80 MHz, 160 MHz (IEEE 802.11ac)
Data Rate	• WCDMA – 384 kbps, HSDPA – 14.4 Mbps (DL) • LTE- 100 Mbps (DL, 2x2 MIMO) • WiBro (802.16 – 50 Mbps (DL, 2x2 MIMO) • LTE-A & WIMAX 802.16m – up to 1 Gbps	• Up to 450 Mbps (IEEE 802.11n) • Up to 7 Gbps (IEEE 802.11ac)
Communication Range	• 10 – 30m	• Up to 100m

Table 3. Femtocell vs. Wi-Fi technology overview [27]

3.2 Review of previous work

In recent years, considerable research effort has been carried out on the investigation of the performance capabilities of Femtocells against Wi-Fi networks, which has yielded an understanding of what these two technologies have to offer.

The concept of Femtocells was pioneered more than a decade ago with Femtocell research starting in the mid 90's through the publication *Analysis of a New Channel Access Method for Home Base Station* building on earlier studies on frequency channel doubly reused cellular systems [29]. This authoritative report described the potential of extending the concept of a home base-station. The author addresses the problem of allocating frequencies in a GSM-based Home Base Station system through a novel solution dubbed "*Total Frequency Hopping"* – a simple architecture of cellular networks. This idea led to suggestions of a requirement to double frequency re-use in both indoor and outdoor environments [29].

Other Publications such as "*Femtocells: Past, Present, and Future"* and "*A Beginner's Guide to Femtocell Technology*" discuss the benefits and growth of Femtocell in the market place and how although it has already outnumbered traditional base stations, questions the legitimacy of this technology, as just a "flash in the pan" spectacle, i.e. an exciting but short period in network evolution that will be rendered obsolete by improved Wi-Fi offloading, new backhaul regulations and pricing, or other unanticipated technological developments [46].

The research paper, *"The comparison between Femtocell and wi-fi"* [47] address the questions "will Femtocells be crucial for offloading data and video from traditional network or will Femtocell deployment prove more trouble than the anticipated, destabilization decades of careful macrocell BS deployment with unpredictable interference while delivering only limited gains"?

More recent research papers "*Interference management in Femtocell-aided cellular networks*"[48] and "*Femtocell versus WiFi – A Survey and Comparison of Architecture and Performance*" [49] address Femtocell systems in a broader manner by delving into the similarities and differences between Wi-Fi and Femtocells. Femtocell versus WiFi – A Survey and Comparison of Architecture and Performance concurs with the notion that although both Femtocells and Wi-Fi can provide convergent communications based on the use of IP networks, considering one technology over the other solely based on technical differences would not yield an optimum wireless communications environment. Interference management in Femtocell-aided cellular networks discusses the major drawbacks of Femtocells, despite their promising advantages, in particular when handling the interference between the macrocell and Femtocell layouts. For example, focusing on closed Femtocells, strong uplink and downlink interference can arise when a macrouser located on the (macro) cell edge radiates at high power while being close to a femto base station, thus potentially disrupting the operation of the Femtocell users [48].

The Naval Postgraduate School in Monterey California published a thesis in 2012 by Mr. James K. Bare titled "*the comparison of performance and capabilities of Femtocells vs Wi-Fi networks"* [60]. The purpose of this thesis was to analyze Femtocell and Wi-Fi network capabilities and performance to determine which is the better platform for military use in a potential tactical network. The author James K. Bare achieves this by comparing performance tests of both technologies in areas of Internet connectivity, uploading and downloading speeds, and Voice over IP (VoIP) in both ideal conditions and in realistic (less than ideal) conditions. The thesis concludes after a series of experimentation that Wi-Fi has a slight but only negligible edge over Femtocells in terms of performance issues.

The hardcover textbooks "*Femtocell Communications and Technologies: Business Opportunities and Deployment Challenge*s" [50] and "*Femtocells: Technologies and Deployment*" [51] discuss extensively the business opportunities and deployment challenges facing Femtocell. The former work focuses on mobility and security in FAPs, cognitive FAPs, and standardization and deployment scenarios. Several crucial topics addressed in these books are network integration option, interference mitigation techniques, optimization, and the economic incentives of installing Femtocells instead of Wi-Fi.

The "*mobile data offloading: Femtocells vs wifi*" [52] tutorial investigates the cost savings associated with operators offloading data with Femtocells as a strategy to bridge the revenue gap. This paper states that operators could save over $30 billion per annum through a Femtocell offloading strategy alone and for operators deploying a Wi-Fi offloading strategy would be saving significantly less (max 25% per annum). Telecommunication industry leaders are still debating the verdict of which technology is the better choice.

Ericsson enterprise solutions division and the Nokia technology alignment have stated that Wi-Fi is the better solution of choice among enterprise vendors because it's relatively cheaper in comparison to the Femtocell as configuring a wireless network that is robust enough to deliver quality voice over cell phones is expensive. The Nokia technology alignment also echoed the idea that Wi-Fi would be more acceptable than Femotocells in both corporate and consumer households because so much other data is transmitted via Wi-Fi making the offer of converged services easier [55].

Also, a significant number of telecom hardware-manufacturers such as Qualcomm and Texas Instruments have failed to get excited about Femotocells, stating "*Femtocells may cause management and interference problems which may lead to creation of gaps in the macro coverage*". With manufacturers displaying a negative response towards the introduction of this technology, it may leave a large gap in the market place that will be filled in by Wi-Fi.

While the manufacturing sectors are still on the fence about the relevance of Femtocells in today's market place, service providers and mobile operators such as Vodafone and T-Mobile are driving the industry development of Femtocells by launching the technology with the aim of delivering cost effective broadband services, and assessing the benefits it can bring to costumers. With T-Mobile leading the Femtocell industry drive, they have been reported as seeing Femtocells having a lot of potential as a solution for mobile operators to boost in-building 3G coverage without the high costs associated with increasing the size of their macro networks.

The Juniper research organization hypothesize that with the increase growth of mobility in wireless communications, by 2015 Wi-Fi and Femtocell will handle almost two thirds (63 %) of the mobile traffic, enforcing the importance of both technologies in telecommunication. This research also states that with Wi-Fi currently handling over 90% of all mobile traffic, Femtocells will have to pick up market share to reach these presumed mobile traffic figures by more mobile operators deploying more Femtocell access points [56].

Industry leader Qualcomm has published a research paper comparing LTE Femtocells operating in close co-ordination along with the macrocell network (Heterogeneous Network) with macrocells augmented by uncontrolled Wi-Fi. This paper states that the technical considerations such as quality of service (QoS), security and mobility need to be taken into account when choosing one technology over the other. This research conducted by Qualcomm delved into the performance comparison between both technologies in two separate scenarios where users on the network were randomly distributed in one case and were then distributed in a cluster close to the FAP and AP in the other case. User experience was encapsulated in the form of user throughput cumulative distributed function (CDF) and was compared for the two scenarios with uniform and non-uniform user distributions within the network. The research concluded that for the same number of small cells in a LTE macro-cell deployment, *co-channel* Femtocells offer a significantly better user experience and system capacity improvement than Wi-Fi APs. In addition, Femtocells also have better support for mobility/handoff, QoS and Security. On the other hand, the research also concluded that Wi-Fi provides a gain in user throughput when a significant portion of user equipment can be offloaded from macrocells to Wi-Fi Aps [10].

3.3 Methodology

The research will be performed using the approach explained in later sections of this dissertation. However, a brief explanation of the approach is given in this section. To obtain a better understanding and analysis of the Femtocell and Wi-Fi network performance, critical evaluations will be based on several systematic performance tests between a Femtocell access point and a Wi-Fi access point in the areas of accessing the Internet, streaming data and voice over IP (VoIP). In order to perform these tests, the required equipment is as follows:

- COTS Wi-Fi access point (802.11 wireless access point),
- COTS Femtocell access point
- A test device
- Cellular Fastlink USB modem
- COTS Router

These equipment will be arranged in the order depicted in figure 16.

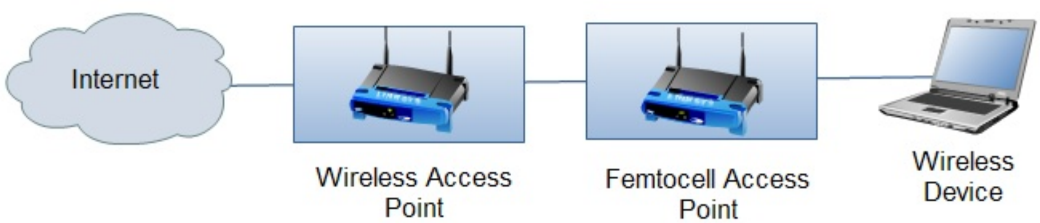

Figure 16. Simplified block diagram of equipment used

3.3.1 Network Configuration

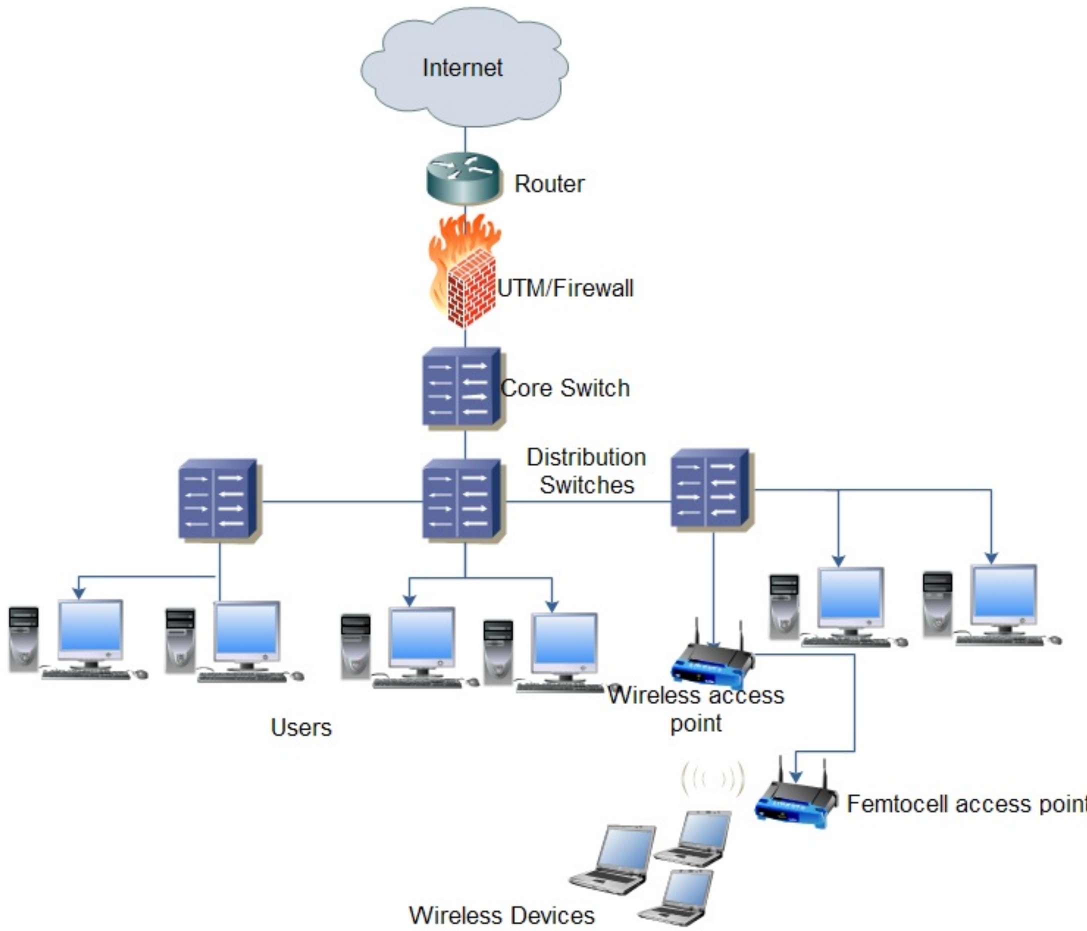

Figure 17. Network configuration

In order to evaluate the performance of a Femtocell network and compare them to those of Wi-Fi network, the testing configuration and environment needs to be stable and experience as little interference as possible from external factors that do not contribute to the objective of the work. The simplest server-client configuration and basic set-up that can provide significant results must be used, as shown in figure 17 above. One test device that acts as the client, a near-by Femtocell or Wi-Fi Access Point connected to a local router that offers access into the IP back- haul, which is then remotely connected to online application server.

Macro- environment level

- Internet: The Internet cloud depicts the source of the Internet

- Router: The Router is a Layer-3 Network device that connects different networks. It acts as a gateway between the LAN and the WAN networks and the Internet. Broadband networks are all terminated on the router.

- UTM/ Firewall: The Unified Threat Management Appliance (or software) is for providing gateway level network security for the various end points used in the organization. The UTM Device provides the following network security options: Firewall, Anti-Virus, Anti-Spam, URL Filtering, Intrusion Prevention (IPS), Content Filtering, Virtual Private Network (VPN) and Protection from Internet threats like Phishing etc. [4].

- Core Switch: A Core Switch is also a Layer-3 based Network Switch that connects to the various distribution switches, edge switches (through distribution switches or directly) using Optical Fiber or Unshielded Twisted Pair (UTP) Copper cabling.

- Distribution Switches (DS): Distribution Switches provide an aggregation layer for network switching. The DS connect to both copper UTP cable network as well as optical fiber networks. They are connected to the core switch on one end and to the edge switches on the other.

Micro – environment level

- Wireless Router: The Wireless Router contains built in radios that provide wireless signals for connecting wireless network devices that posses an in-built wireless adapter.

- Femtocell: a small cellular base station designed for use in residential or small business environments. It connects to the network provider via broadband (such as DSL or cable) and supports multiple devices. A Femtocell allows service providers to extend service coverage where access would otherwise be limited or unavailable without the need for expensive cellular towers. It also reduces backhaul costs as it routes cellular traffic through the IP network.

- Network Endpoints: There are various network devices connecting to the LAN via edge switches and wireless access points. They include PCs, Laptops, PDAs, etc. for data connectivity, IP Phones, Cell Phones, Wi-Fi Phones and Soft Phones for voice connectivity and video over IP applications. There are also network based accessories like network printers, Scanners etc. that may connect to the network.

3.3.2 Technical specifications of devices used

Wireless router

Model	Cisco Linksys WRT160N v3
Standards	Draft 802.11n, 802.11g, 802.11b, 802.3, 802.3u
Antennas Gain in dBi	1.5 dBi
Ports	Power, Internet, and Ethernet (1-4)
Carrier Frequency Bands	2.4 – 2.5 GHz
RF Power in dbm	1.7 dBm
Security features	WEP, WPA, WPA2
Power usage	12V, 0.5A

Table 4. Wireless router specifications

During experimentation, interference from other Wi-Fi APs is not going to be modeled assuming there is intelligent channel selection or there has been some Wi-Fi network planning done in the environment.

Femtocell access point

Frequency	800/1900MHz
Air interface	CDMA2000 1x Rel 0 CDMA2000 EvDO 0/A
Transmission	10/100 Base-T Ethernet/Network
Standards	IEEE 802.3, IEEE 802.3u for Ethernet IEEE 802.11g, IEEE 802.11b for Wireless
Power Usage	10 mW to 30 mW
Baseband capacity	Maximum ten devices with each connection supporting a simultaneous voice call and data session

Table 5. Femtocell access point specifications

An IEEE Channel model D is chosen for the simulations. This channel model has been extensively validated in the research paper "*Simulation Research of 802.11n Channel Model D in NS2*" for use in standard enterprise and residential environments [57].
The first series of tests will be baseline performance tests that will establish the basic performances in an ideal condition. Following a repeat of the same series of tests, but in a realistic environment (non-ideal situations). As stated earlier, targeted areas of testing include accessing the Internet through Hyper Text Transfer Protocol (HTTP), streaming data through Real-time Transport Protocol (RTP), and voice over Internet protocol (VoIP) through SIP and UDP. These three testing areas were selected because they use several protocols that encompass the everyday use of a wireless network. They not only represent the bulk of the actual data moved over a Femtocell or Wi-Fi network, but they also include the supporting protocols that are most likely to be part of any protocol mixture required to run most applications.

Testing will be done in the following order:

"Accessing the Internet through HTTP" would be the first area of testing. HTTP being the webs application-layer protocol is at the heart of the World Wide Web. HTTP defines the structure in which client program and server program messages are formatted and

transmitted and also what actions web servers and browsers should take in response to given commands [4].

RTP is the underlying protocol used in "*streaming of data"*. It defines a standardized packet layout for delivering audio and video over IP networks. RTP itself does not guarantee real-time data delivery, but it provides the mechanisms for sending and receiving applications to support streaming data. It is extensively used in multimedia applications such as streaming media, teleconferencing, and real time data sharing [4].

The final area of testing shall be "*VoIP"*. VoIP is a method of transmitting voice communications and multimedia sessions over IP-based networks. The steps involved in originating a VoIP session are signaling and media channel setup, changing the analog voice signal to a digital format, encoding and transmission of IP packets over a packet-switched network [4].

3.3.3 Testing Parameters

To accomplish the goal of this investigation, the research should accurately evaluate the performance and capabilities of both technologies, starting with baseline tests. As stated, the testing will be conducted in various conditions consisting of the evaluation of the networks in less than ideal environment for optimal transmission. An ideal environment is one where the test device and the access points have minimum interference between sent and received signals. The non-ideal environments consist of larger distances between the router and FAP, line-of-sight obstacles, and a combination of both.

The number of users on the network will not be included in the experiments as any variation or introduction of extra users in the configuration may alter the results by creating additional unwanted traffic.

After initial sets of baseline tests, subsequent tests for the various applications and conditions will be evaluated and compared with respect to these baseline tests results. This places emphasis on the differences in terms of comparative performances. For instance, Femtocell initial technical specifications show that Femtocell technology has less speed and bandwidth than Wi-Fi technology, this will reflect in the baseline tests, but what this investigation aims to identify is the applications and conditions for which Femtocells and Wi-Fi exhibit significant improvement or regression in performance in comparison with the initial baseline tests.

Each experimental subgroup will include a set of representative tests. These tests are performed in order to ascertain which areas differ between Femtocells and Wi-Fi performance. They include:

1. Ping/Latency Test: A ping test is a network administration utility that determines whether a device can communicate with another device over a network. Simply put, it is a process where one device sends an echo-request packet also known as an Internet Control Message Protocol (ICMP) to a different or remote target device. The time between when the request (or ping) is transmitted and the acknowledgment of the associated echo-reply is a measurement of the latency of the connection. *Latency* can be defined as the delay that occurs during the performance of a given operation. It is the interval between the time a service request is made by an associated device and the time it receives a response from the system. If the user experiences a delayed response it means that there is a higher than desired network latency [58].

2. Jitter Test: Jitter can be defined as an undesired deviation from true periodicity of an assumed periodic signal, or in this case, a ping. A jitter test would measures the packet delay variance (PDV) in successive ping tests. For

this measurement, the difference in delay between subsequent packets that arrive at a particular host is compared. A zero reading is ideal, meaning the echo-requests results have no delay. A low reading in a jitter test means that the difference in delay is fairly small, while a high score indicates problems in the network, which may be caused by higher than desired network latency. The lower the jitter value the better the QoS for applications sensitive to delay [59].

3. Packet loss Test: Packet loss is the term used when a transmitted packet that is sent over the network does not reach its destination host. If a transmitted packet does not reach its destination host within a reasonable time frame, that packet is also considered to be lost. A lost packet could have been blocked at an intermediate router due to congestion, or excessively delayed due to queuing in the router, or incorrectly routed due to some error. Having lost packets may be a result of there being a fault associated with the network connection, congested network sections or unreliable network paths. Packet losses reduce upload and download efficiency due to requirements for retransmissions by applications sensitive to packet loss, leading to poor quality VoIP audio, and pauses in streaming media. A packet loss test result would be expressed as a percentage of the packets considered as lost, against the total number of packets processed for a particular time frame. This is known as the Packet Loss Ratio (PLR) [59].

4. Packet order test: This test is the measure (in percentage) of the amount of packets that have arrived in order. Data packets do not necessarily take the same routes or arrive at the same time when transmitted. This result in packets arriving out-of-order which delays scheduled packets meant for delivery, also causing packet losses. Delayed or lost packets that result from

out-of-order packets may cause performance problems that could lead to increased retransmissions, which worsens network performance issues [59].

5. Packet discard test: this test is the measure of packets that arrive too late to be used by the application. While packet loss is directly related to an Internet connection (transmitted but not received packets that are considered “lost” may be the fault of equipment and can be resolved by the network service provider), packet discard on the other hand is a direct result of latency and jitter. Packet arrivals may be time sensitive, especially with respect to media based applications, such as audio or steaming-video. When packets are sent, due to latency or wrong routing, they may not all arrive at the destination in the correct order, the packets that arrive late are considered "discarded". If a packet arrives too late and is discarded, the application performance suffers, effectively wasting the network resources that were used to deliver it [59].

6. Download and Upload Speed Test: this test is aimed at measuring how fast a user’s connection can deliver content to and from a computer. This is the relative measure and not the theoretical value for the link. To achieve the optimal delivery of information for applications like VoIP, email, and on-line interactive programs, the receiving party’s download rate must be at least as fast as the sending party’s upload rate. In most cases uploading files is slower than downloading files. This is due to the fact that most Internet connection devices are designed to provide better downloading rates than upload rates. The reason for this is that most users spend the majority of their time on the Internet viewing web pages or using multimedia files which involve downloading [59].

7. Round trip time (RTT) test: This is the time it takes for a packet to be sent end-to-end between the client and the server and for a response to be

received back from the recipient i.e. when a client sends a packet and requests an immediate response form the server. The client device measures from the start of the transmissions to the end of the received response packet form the server. Packet delay (the time taken for a packet to travel from the source host to the destination host through the network) can then be calculated as half of the round trip time, under the notion that the forward and reverse paths have the same characteristics i.e. length, bitrate capacity and load. A long round trip time will significantly slow connection throughput performance, and an erratic round trip time is an indication of network congestion problems [4].

3.4 Conclusion

This chapter serves as a basic introduction to the subject of Femtocells vs. Wi-Fi technology, and validates the need for this investigation by providing an overview of the problem statement, the objectives of the research and the methodology used in the experimentation that investigate the problem. It includes the technical differences of both technologies, the methodology of the experimentation and the configuration of the devices used in testing. It also includes previous work done on the subject which shows that a vast amoutnt of research effort has been put into the investigation of Femtocells against Wi-Fi. As demand grows for wireless services, it ceases to be simply about providing the services but how efficient and effective these services are and how an operator can keep a competitive edge while providing these services. This chapter validates the need for further investigation into Femtocells and wi-fi networks.

4. Experimentation

4.1 Introduction

For the analysis, four different testing conditions are considered to best represent a realistic environment. These conditions will vary in distance from the access points and would include strategic placements of obstacles in the form of walls and line-of-sight obstacles.

In the first condition, the test commenced in an indoor area 7.5 meters away from the WAP and FAP with a non- supporting wall between the access points and the testing device; see figure 18.

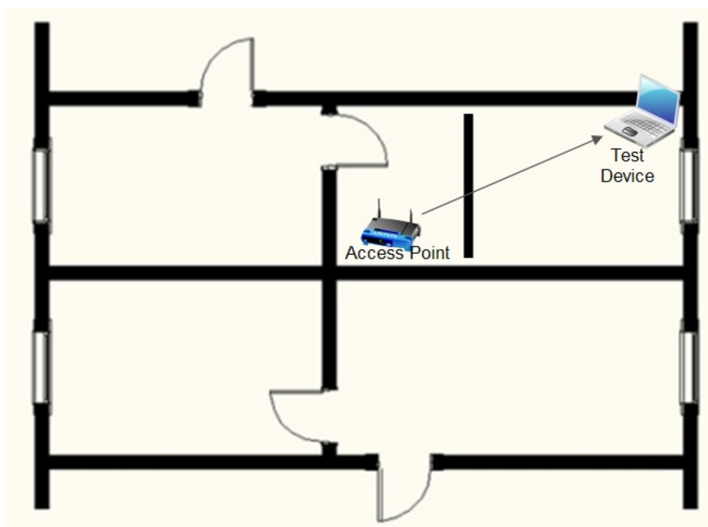

Figure 18. Test 1 scenario

The second test condition takes place in the same distance of 7.5 meters with the test device being moved to another area in the building, while the access point remains undisturbed. In this case, there is both a non-supporting and a supporting wall between the access points and the test device.

In the third condition, the test device remains in a separate room with both a non-supporting and a supporting wall between the access point and the test device, but with a distance of 15 meters between them; see figure 18.

Finally, in the last condition, the test device still will remain in a separate room and continue to have both non- supporting and supporting walls between the access point and the test device but with a distance of 23 meters between them.

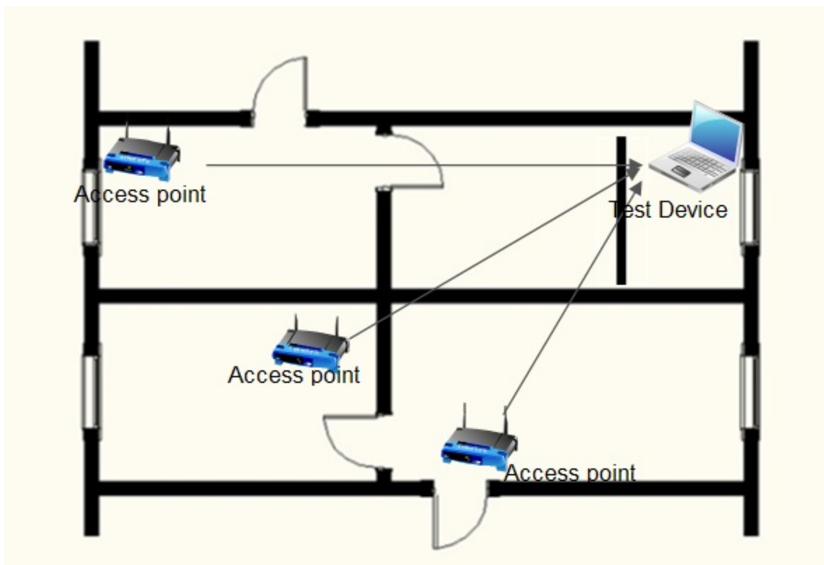

Figure 19. Test 2 - 4 scenario

The results presented for each condition and specific test vary for both technologies and in the comparison of these results, this investigation aims to disclose how each technology performs under these conditions and also answer the key research question. All experimentation is done at the University of Witwatersrand CeTAS and the MTN Telecommunications innovation center Laboratories.

4.2 Baseline testing in Ideal environment

As stated in previous sections, testing begins with establishing control parameters. This is achieved by performing baseline tests. Baseline tests are tests conducted before the realistic field-like condition tests in order to establish preliminary parameters in near ideal settings. These tests are performed to ascertain the best-case values that are achievable by each respective technology. These baseline tests will also identify the basic differences between Femtocell and Wi-Fi technologies as they are designed to address the network parameters (download and upload speeds, packet losses and transfers, round-trip-time, jitter, etc.) under ideal channel transmissions i.e. no delays, imperfections or signal interference. Results of testing in ideal conditions will be used as reference points for successive testing.

4.2.1 preliminary assumptions

In order to achieve significant results during baseline testing, certain predetermined conditions need to stated:

- Assumption of an ideal channel: Transmission channel is assumed to have no delays, imperfections or signal interference, i.e., the transmission parameters are best possible***.***
- Assumption of normal traffic conditions***:*** it is assumed that sending and receiving data occurs with no additional source of traffic; i.e. testing is achieved without less or additional data traffic.

In other words, there should be no resource sharing or interference between the Femtocell and Wi-Fi access points as in the 4G cellular network and the Wi-Fi network function on separate frequency bands.

4.2.2 Software Used

- Pingtest.ne: Pingtest.net is an online performance-measuring tool that determines the quality of a broadband Internet connection, in regards to latency. This is done through the measurement of packet loss, ping and jitter. The values of these measurements give an overall grade of A – F (A being the highest grade and F being the lowest grade) of the tested broadband quality.

– Speedtest.net: Speedtest.net is also an online performance measuring tool that tests Internet connection bandwidth in regards to upload and download performances in different locations i.e. between the client and the remote server hosting the speedtest application.

– Ping-test.net: Ping-test.net is another online performance measuring tool that tests the speed and performance of an Internet connection. This test is achieved by checking the speed a user uses in downloading and uploading data. This is done by the transmission of various sized data packets through the Internet connection and measuring the speed it takes to reach its destination. Small sized packets are transmitted much quicker than large sized packets, although large sized packets are transmitted far more frequently in everyday web browsing.

4.2.3 Upload/Download speed test using Speedtest.net

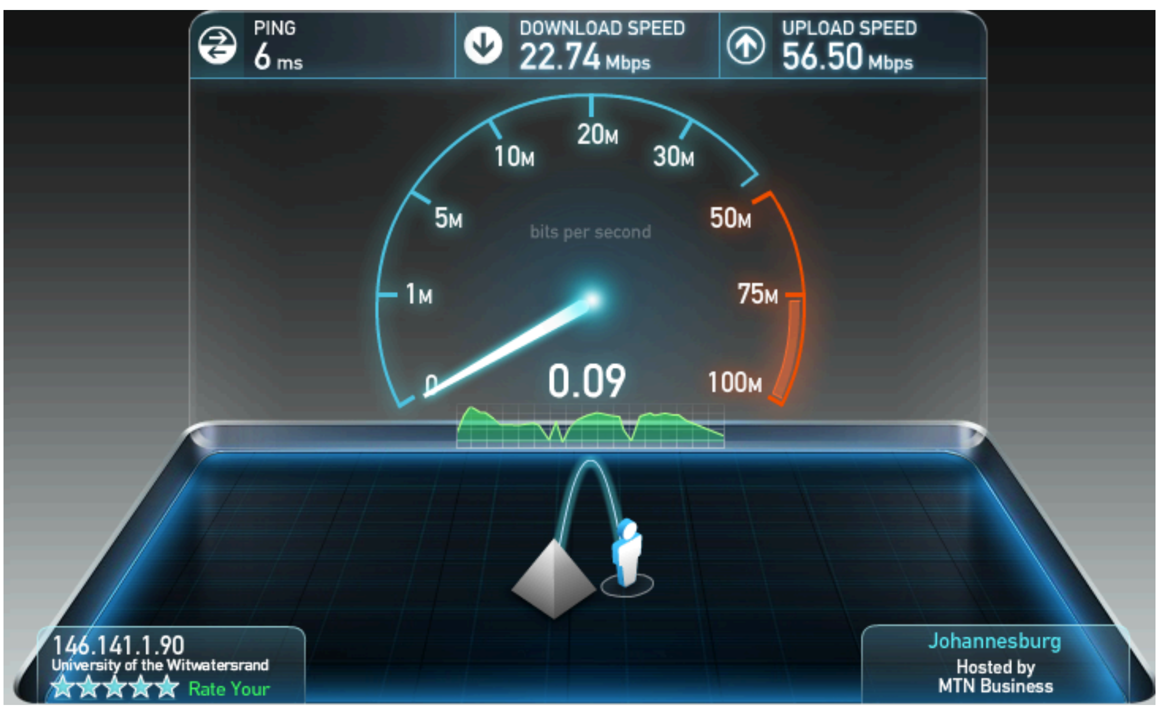

Figure 20. Wi-Fi speedtest.net connection

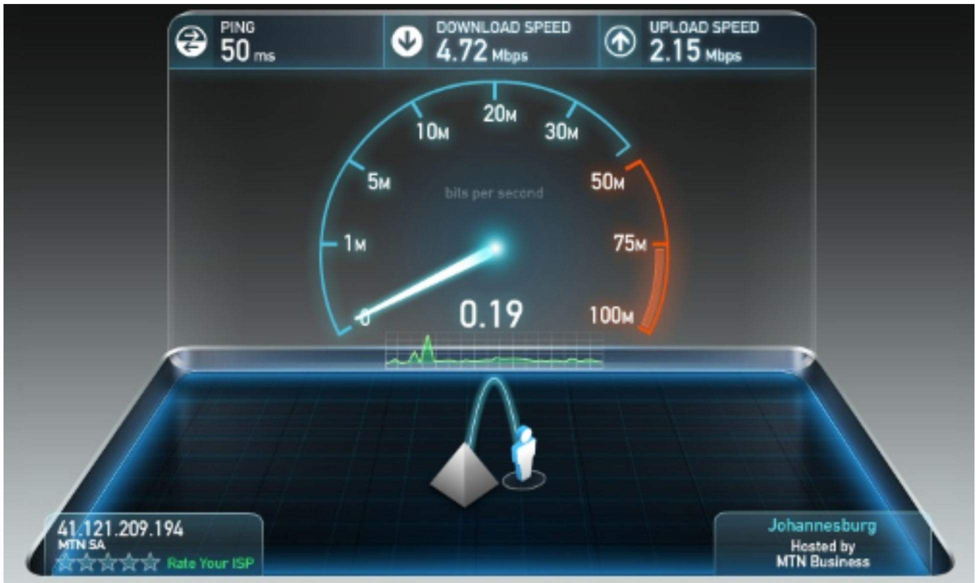

Figure 21. Femtocell speedtest.net connection

Technology	Ping average (ms)	Download speed average (Mb/s)	Upload speed average (Mb/s)
Wi-Fi	24.6ms	20.27mb/s	4.18mb/s
Femtocell	48.1ms	11.12mb/s	0.47 mb/s

Table 6. Wi-Fi and Femtocell speedtest.net connection average results

4.2.4 Ping, Jitter and Packet loss test using Ping-test.net

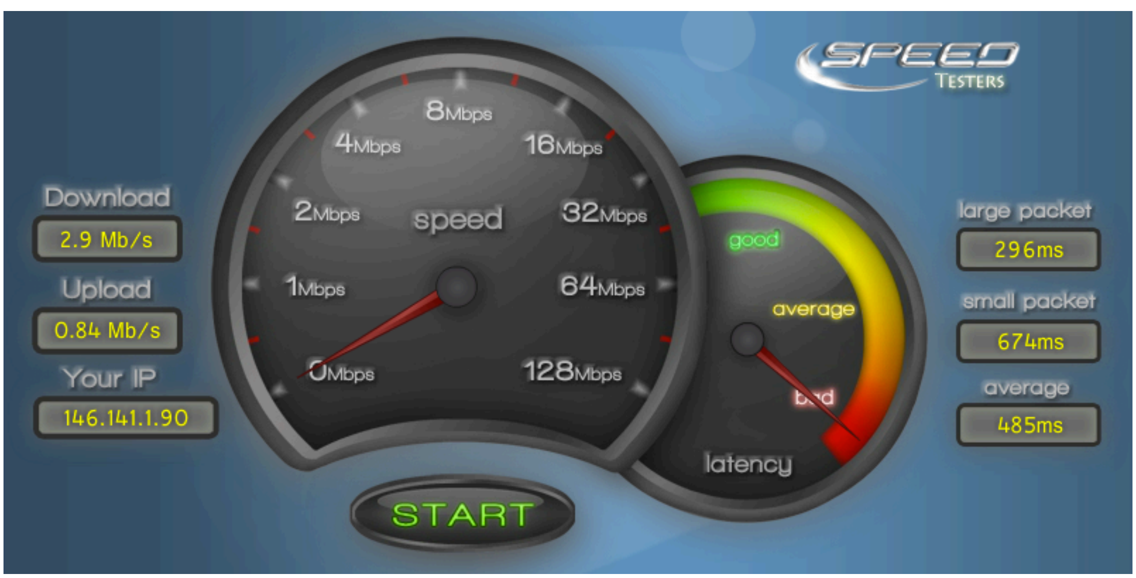

Figure 22. Wi-Fi ping-test.net connection

Figure 23. Femtocell ping-test.net connection

Technology	Download speed average (Mb/s)	Upload Speed average (Mb/s)	Ping: Large packets average (ms)	Ping: small packets average (ms)	Average Latency average (ms)
Wi-Fi	2.9mb/s	0.87mb/s	294.33ms	683ms	482ms
Femtocell	1.7mb/s	0.29mb/s	163.83ms	89.3ms	143.1ms

Table 7. Wi-Fi and Femtocell ping-test connection average results

4.2.5 Ping, Jitter and Packet loss test using Pingtest.net

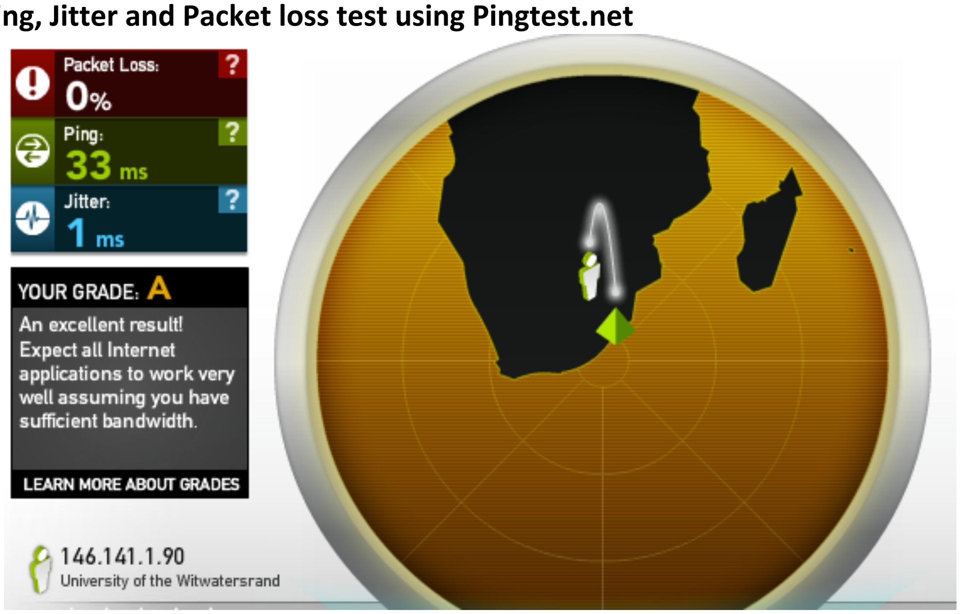

Figure 24. Wi-Fi pingtest.net connection

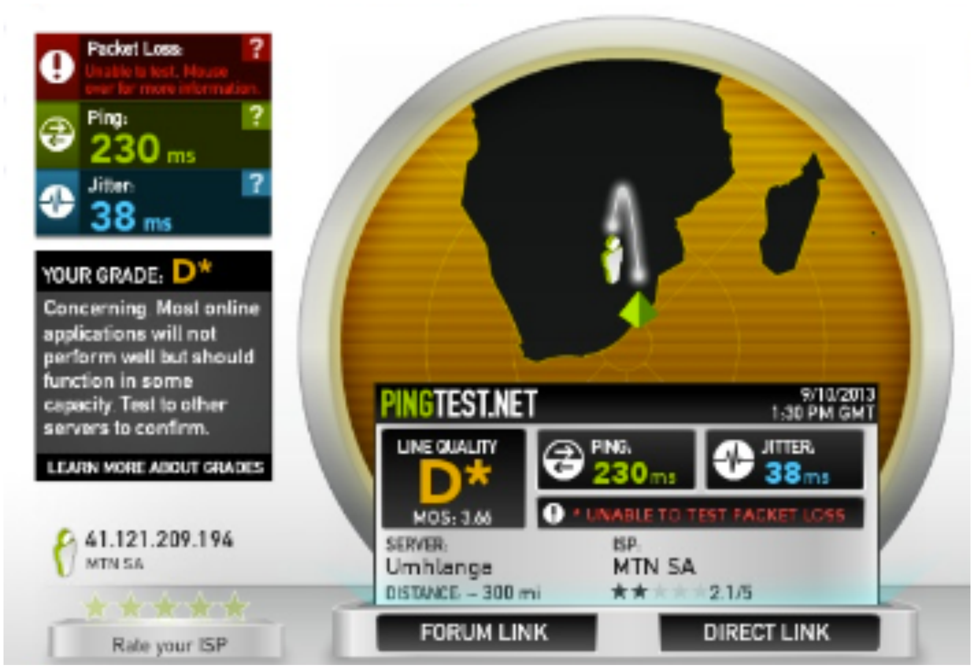

Figure 25. Femtocell pingtest.net connection

Technology	Packet loss average (%)	Ping average (ms)	Jitter average (ms)	Score average (/5)
Wi-Fi	0%	28.1ms	8ms	4.3
Femtocell	0%	48.6ms	12.8ms	3.3

Table 8. Wi-Fi and Femtocell pingtest.net connection average results

4.2.6 Baseline Test Assessment

The Baseline test results show expected consistency with regards to the Femtocell and IEEE 802.11 Wi-Fi principles that govern each technology. Through each iteration and software tool used, it can be observed from the overall averages that Wi-Fi outperforms Femtocells in areas of basic speed and packet transmission, as Wi-Fi's downloading speed exceeds that of the Femtocell's. This is also evident in the uploading speed results, as Wi-Fi shows it is faster than the Femtocell. This is due to the channel capacities for both technologies operating in two different schemes.

4.2.7 Wi-Fi and Femtocell operational differences

The IEEE 802.11 Wi-Fi operates in the same frequency channel for uploading and downloading data packets. This is achieved through channel partitioning protocols. Wi-Fi technology was designed to operate utilizing a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) channel partitioning protocol. This *random access* protocol dictates that there must be fair access to resources as the transmission channel is shared; meaning that each user terminal senses the channel before transmitting data and also refrains for transmitting data when it senses the channel is busy [4].

On the other hand, Femtocells mode of operation is completely differently form Wi-Fi in the sense that they utilize different channels for uploading and downloading data packets. This means the downloading speed and the uploading speed are independent from each other [46].

These basic operating differences need to be well considered when identifying which technology to adopt for which environment with regard to the amount of data being transmitted. Another area of interest that should be noted is the packet transit route taken by each technology. The longer route consequently gives the longer transit time for data to reach its destination. Transit time is determined by the RTT. This is time needed to transfer the packet locally over-the- air, i.e. across the entire chain, from device to server and back for both the Femtocell and Wi-Fi network.

In the case of the Femtocell, data has to travel from the Home Node B (HNB), through the user IP broadband connection, then through the HNB gateway (HNB GW), then through the mobile operators infrastructure, then through the IP global network before reaching the application server. These steps must be repeated in reverse for data to travel back to the initial transmitting device. While in the case of the Wi-Fi, data travels from the Wi-Fi Router, through the IP global network and then the application server. This additional operational difference also needs to be taken into consideration when choosing between the two technologies as it implies that Femtocells having the more complex back-end architecture, will exhibit an inherent larger delay in transit or RTT[46].

Finally, examining the jitter results reveals that the Femtocells Jitter is not much higher than the Wi-Fi Jitter. As jitter measures the packet delay variance (PDV) in successive ping tests, the results indicate that although Femtocells may be slower in communications, they do maintain stable and steady transmission in comparison to Wi-Fi transmissions.

4.3 Testing in realistic environments

The previous section provided a general overview with regards to the differences in between Wi-Fi and Femtocell performance under ideal conditions. These results are a good baseline for the next set of tests as they eliminate the possible "faultless condition" results, leaving only the realistic measurements. Most day-to-day residential or enterprise wireless data transmissions are used in less than ideal conditions, as access points may be located several meters from user equipment with various obstacles such as walls separating them.

4.3.1 Software Used

- Wi-Fi SiStr: Wi-Fi SiStr is a freeware Wi-Fi analyzer that enables the user to keep track of the Wi-Fi networks signal strength by means of an easy to use graphic user interphase (GUI). It updates the signal strength in real time, providing accurate information on the tested Wi-Fi network.

- Open Signal Map: Open signal map is a free Cellular signal analyzer that Supports GSM, CDMA, 4G, 3G and 2G devices. It allows the user to map the location of the cell tower that the mobile phone is connected to, test the connection speed and measure the exact signal strength in real time providing accurate information on the tested Femtocell network.

4.3.2 Obstacle Influence

The performance of a Wi-Fi or LTE Femtocell network connection depends on the signal strength between a user device and the access point. The level of signal strength determines the data rate achievable for that connection. Signal strength may be reduced by the attenuation caused by obstruction of the transmission path i.e. signals being blocked off by floors, walls and other structures. Thus, before proceeding with the realistic baseline tests, it is necessary to evaluate the signal strength in ideal conditions using the described software in order to get comparable results.

Test	Wi-Fi signal Strength (dB)	Femtocell signal Strength (dB)
Baseline Test (access point less that 1meter away and no obstacles)	-33dB	-51dB
Scenario 1 (access point 7.5 meters away and non-supporting wall obstacle)	-66dB	-75dB
Scenario 2 (access point 7.5 meters away and non-supporting and supporting wall obstacle)	-70dB	-81dB
Scenario 3 (access point 15 meters away and non-supporting and supporting wall obstacle)	-75dB	-88dB
Scenario 4 (access point 23 meters away and non-supporting and supporting wall obstacle)	-80dB	-95dB

Table 9. Wireless signal strengths

As the table 9 shows, signal strength reduces the further away the device is from the access point, as wireless signals cannot travel indefinitely through the air because they eventually disperse and get absorbed by the surrounding environment. These signals further reduce once there is any form of obstruction such as supporting and non-supporting walls and floors between the transmitting access point and the receiving end node leading to an overall reduced RSS.

4.3.3 Upload/download speed test using speedtest.net in realistic scenarios

- Scenario 1

Technology	Ping average (ms)	Download speed average (Mb/s)	Upload speed average (Mb\s)
Wi-Fi	23.33ms	12.51mb/s	7.83mb/s
Femtocell	150ms	6.45mb/s	0.96mb/s

Table 10 Scenario 1 Wi-Fi and Femtocell speedtest.net connection average results

- Scenario 2

Technology	Ping average (ms)	Download speed average (Mb/s)	Upload speed average (Mb\s)
Wi-Fi	31.8ms	16.88mb/s	4.29mb/s
Femtocell	578.6ms	11.92mb/s	1.07mb/s

Table 11. Scenario 2 Femtocell speedtest.net connection average results

- Scenario 3

Technology	Ping average (ms)	Download speed average (Mb/s)	Upload speed average (Mb\s)
Wi-Fi	25ms	13.75mb/s	3.75mb/s
Femtocell	557ms	11.2mb/s	1.01mb/s

Table 12. Scenario 3 Wi-Fi and Femtocell speedtest.net connection average results

- **Scenario 4**

Technology	Ping average (ms)	Download speed average (Mb/s)	Upload speed average (Mb\s)
Wi-Fi	25ms	9.47mb/s	4.74mb/s
Femtocell	339.33ms	4.64mb/s	0.51mb/s

Table 13. Scenario 4 Wi-Fi and Femtocell speedtest.net connection average results

4.3.4 Realistic Test Assessment

Test	Ping (ms)	Download speed (Mb/s)	Upload speed (Mb/s)	Signal Strength (dBM)
Baseline	24.6ms	20.27mb/s	4.18mb/s	-33dB
Scenario 1	23.33ms	12.51mb/s	7.83mb/s	-66dB
Scenario 2	31.8ms	16.88mb/s	4.29mb/s	-70dB
Scenario 3	25ms	13.75mb/s	3.73mb/s	-75dB
Scenario 4	25ms	9.47mb/s	4.74mb/s	-80dB

Table 14. Wi-Fi averages for realistic scenarios

Test	Ping	Download speed (Mbs)	Upload speed (Mbs)	Signal Strength (dBM)
Baseline	48.1ms	11.12mb/s	0.47mb/s	-51dB
Scenario 1	150ms	6.45mb/s	0.96mb/s	-75dB
Scenario 2	578.6ms	11.92mb/s	1.07mb/s	-81dB
Scenario 3	557ms	11.42mb/s	1.01mb/s	-88dB
Scenario 4	339.33ms	4.64mb/s	0.51mb/s	-95dB

Table 15. Femtocell averages for realistic scenarios

Upon examining the results in the tables 14 and 15, the realistic scenarios show that Femtocells are quite resilient when it comes to distance and obstacles hindering communications. The Femtocell has much higher received signal strength (RSS) when compared to that of the Wi-Fi connection in all four scenarios. It can be noticed that the Wi-Fi performance declines as the scenarios become tougher for wireless communications to operate efficiently.

From scenario 1, it can be seen in table 14 and 15 that by the addition of a non-supporting wall at a distance of 7.5 meters has a significant effect on the Wi-Fi and Femtocell signal as RSS is lowered, but the Femtocell signal is slightly more resilient.

From scenarios 2 – 4, it can be seen in table 15 that the Femtocell results are considerably greater than that of the Wi-Fi. Though as mentioned in previous chapters, attenuation of electromagnetic signals are more prominent at higher frequency bands, Wi-Fi systems operate on a 2.4GHz band and Femtocell systems operate on a 1.8GHz band, thus, the above scenario results were expected as the Femtocell carrier frequency is lower than that of the Wi-Fi.

It can be seen in table 15 that by the addition of the supporting wall and the non-supporting wall, there is very little impact on the Femtocell signal, but there is a significant drop in that of the Wi-Fi signal for all given scenarios except scenario 4 where both Femtocells and Wi-Fi show significant drops in RSS.

The realistic environment testing revealed the effects of distance and obstacles on the signal strength of both technologies but as the results show, it is more prominent in Wi-Fi than it is in Femtocell signals. In contrast with our baseline tests, the performance of Wi-Fi uploading and downloading speeds is significantly less when operating in a realistic environment showing that Femtocells are capable of better wireless transmissions in less than ideal environments.

4.4 Testing Web access through HTTP

Hypertext Transfer Protocol (HTTP) is the underlying application- layer protocol used by the World Wide Web. It's a stateless respond/request protocol, i.e. web browsers initiate a request command to a web server; the web server then sends back the appropriate response to the web browser, providing an information pull service.
HTTP being a stateless protocol means that Web browsers and servers interchange information independently in accordance with the rules established by HTTP.
HTTP also defines how messages are formatted and transmitted and what action browsers and web servers should take in response to various commands. Each command is executed independently in order to transfer data to the Internet.
Testing here addresses HTTP downloading and fleshes out the differences between the capabilities of Wi-Fi and Femtocells in terms of downloading data from the Internet [4].
Note: All testing is done in realistic conditions of scenario 2.

4.4.1 Software used

- Downtester: Downtester is freeware that tests Internet download speed in multiple locations round the world. It automatically tests the download speed of predetermined URLs systematically, i.e. Downtester moves to the next download URL after a predetermined time has been lapsed or after it the specified amount of data has completely downloaded.
  For this investigation, Downtester will be used to measure the time to download files that are 20 MB, 50MB, 100MB, and 200MB in size. These sizes represent the average web users downloading need.

- HTTP Scoop Analyzer: HTTP Scoop is a real time HTTP monitoring tool also known as HTTP protocol analyzer or HTTP sniffer and is used for debugging proxies which logs all HTTP(s) traffic between your computer and the Internet. HTTP Scoop records all HTTP traffic that passes between device and server.

4.4.2 HTTP Download/Upload Tests Results

Downtester is opened and, the URL of the file to be downloaded is input, the link of the 20MB test file is input five times. The software is then launched and will execute the download five consecutive times and register the results systematically. This procedure is then repeated for the other file sizes (50MB, 100MB and 200MB) respectively for both Wi-Fi and Femtocell with the average results compiled and compared.

- Results for Downtester.net 20MB file

Technology	Speed average (Kbytes/s)	Speed average (Mbits/s)
Wi-Fi	902.35kb/s	7.70mb/s
Femtocell	481.33kb/s	4.02mb/s

Table 16. Wi-Fi and Femtocell connection average results 20MB file

- Results for Downtester.net 50MB file

Technology	Speed average (Kbytes/s)	Speed average (Mbits/s)
Wi-Fi	987kb/s	8.2mbps
Femtocell	537kb/s	4.6mbps

Table 17. Wi-Fi and Femtocell connection result 50MB file

- Results for Downtester.net 100MB file

Technology	Speed average (Kbytes/s)	Speed average (Mbits/s)
Wi-Fi	984.3kb/s	7.90mbps
Femtocell	505.7kb/s	4.84mbps

Table 18. Wi-Fi and Femtocell connection result 100MB file

- Results for Downtester.net 200MB file

Technology	Speed average (Kbytes/s)	Speed average (Mbits/s)
Wi-Fi	401.38kb/s	3.83mb/s
Femtocell	230.8kb/s	1.7mbps

Table 19. Wi-Fi and Femtocell connection result 200MB file

4.4.3 HTTP Monitoring in Real time

For the real time monitoring of HTTP traffic, we utilize HTTP Scoop – a free HTTP analyzer. For the analysis, we shall consider the top six visited websites in South Africa according to the web information company www.alexa.com.

- www.google.co.za
- www.facebook.com
- www.youtube.com
- www.amazon.com
- www.yahoo.com
- www.gumtree.co.za

These six websites all contain similar content, not that they are all identical, but "content" in the sense that they all posses data, images, video and applications. Although there is similarity, the way the files are handled and the susceptibility to loss or delay of data packets is particular to specific file types, based on the requirements of using applications.

Time	Method	Request URL	Content Type	Size (KB)	Status	Code
13:40:04:767	GET	http://facebook.comhttp://facebook.com/	text/html	1.28	Done [0.001s]	407
13:40:04:769	GET	http://facebook.comhttp://facebook.com/	text/html	1.28	Done [0.001s]	407
13:40:04:770	GET	http://facebook.comhttp://facebook.com/	text/html; charset=utf-8	0	Done [0.960s]	301
13:40:05:731	GET	http://www.facebook.comhttp://www.facebook.com/	text/html; charset=utf-8	133.45	Done [4.560s]	200
13:40:07:243	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yQ/r/H5HF20X8Z5g.css	text/html	1.40	Done [0.002s]	407
13:40:07:244	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yD/r/OWwnO_yMqhK.css	text/html	1.40	Done [0.003s]	407
13:40:07:244	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yz/r/gKQmz6ilc-T.css	text/html	1.40	Done [0.003s]	407
13:40:07:244	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/ys/r/q06xtvOJF0F.css	text/html	1.40	Done [0.003s]	407
13:40:07:245	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yS/r/AXbdtQOFsWr.css	text/html	1.40	Done [0.003s]	407
13:40:07:246	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yC/r/fTIMMkGaEM2.js	text/html	1.39	Done [0.003s]	407
13:40:07:250	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yQ/r/H5HF20X8Z5g.css	text/html	1.40	Done [0.001s]	407
13:40:07:250	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yz/r/gKQmz6ilc-T.css	text/html	1.40	Done [0.001s]	407
13:40:07:251	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yD/r/OWwnO_yMqhK.css	text/html	1.40	Done [0.002s]	407
13:40:07:252	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/ys/r/q06xtvOJF0F.css	text/html	1.40	Done [0.001s]	407
13:40:07:253	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yC/r/fTIMMkGaEM2.js	text/html	1.39	Done [0.002s]	407
13:40:07:253	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yS/r/AXbdtQOFsWr.css	text/html	1.40	Done [0.002s]	407
13:40:07:255	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yQ/r/H5HF20X8Z5g.css	text/css; charset=utf-8	45.72	Done [0.064s]	200
13:40:07:256	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yD/r/OWwnO_yMqhK.css	text/css; charset=utf-8	0.50	Done [0.000s]	200
13:40:07:257	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yz/r/gKQmz6ilc-T.css	text/css; charset=utf-8	33.15	Done [0.063s]	200
13:40:07:308	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yC/r/fTIMMkGaEM2.js	application/x-javascript;	21.74	Done [0.013s]	200
13:40:07:311	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/ys/r/q06xtvOJF0F.css	text/css; charset=utf-8	1.06	Done [0.002s]	200
13:40:07:313	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yS/r/AXbdtQOFsWr.css	text/css; charset=utf-8	0.30	Done [0.001s]	200
13:40:07:748	CONNECT	http://fbcdn-profile-a.akamaihd.netfbcdn-profile-a.akamaihd.net:443	text/html	1.32	Done [0.004s]	407
13:40:07:748	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yJ/r/TOn8ZOS9JFf.js	application/x-javascript;	70.90	Done [0.017s]	200
13:40:07:750	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/ym/r/bJENKpjuiw0.js	application/x-javascript;	32.22	Done [0.013s]	200
13:40:07:754	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yS/r/3JJjN2gY90P.png	image/png	11.79	Done [0.010s]	200
13:40:07:756	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/y9/r/jKEcVPZFk-2.gif	image/gif	1.73	Done [0.002s]	200
13:40:07:756	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yb/r/GsNJNwul-UM.gif	image/gif	0.51	Done [0.000s]	200
13:40:07:757	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yL/r/dEtDbeA_dxm.png	image/png	12.62	Done [0.003s]	200
13:40:07:767	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yg/r/Qdv04UHuWZa.png	image/png	0.30	Done [0.000s]	200
13:40:07:767	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yW/r/FGGkNcHydm2.css	text/css; charset=utf-8	5.31	Done [0.001s]	200
13:40:07:768	CONNECT	http://fbcdn-profile-a.akamaihd.netfbcdn-profile-a.akamaihd.net:443	text/html	1.32	Done [0.002s]	407
13:40:07:769	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yO/r/rfFO0dqI-dD.png	image/png	76.90	Done [0.035s]	200
13:40:07:771	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yl/r/aoGVaWCuzdk.png	image/png	9.13	Done [0.025s]	200
13:40:07:793	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yP/r/VximzNmqywk.png	image/png	9.98	Done [0.004s]	200
13:40:07:795	GET	http://static.ak.fbcdn.nethttp://static.ak.fbcdn.net/rsrc.php/v2/yw/r/GKHreilWaRT.png	image/png	0.22	Done [0.001s]	200
13:40:07:804	CONNECT	http://fbcdn-profile-a.akamaihd.netfbcdn-profile-a.akamaihd.net:443		0	Done [0.000s]	200
13:40:07:804	Qå16KYù´=	http://146.141.1.99ÀÀÀÀÀÀÀÀÀÀÀÀÀ		0	Reset by peer	

Figure 26. HTTP scoop for facebook.com using Wi-Fi connection

HTTP Scoop breaks the content of these websites into percentages of the total amount of components that make up the site. These percentages shall then be used as reference when breaking down the websites into four phases of the HTTP request.

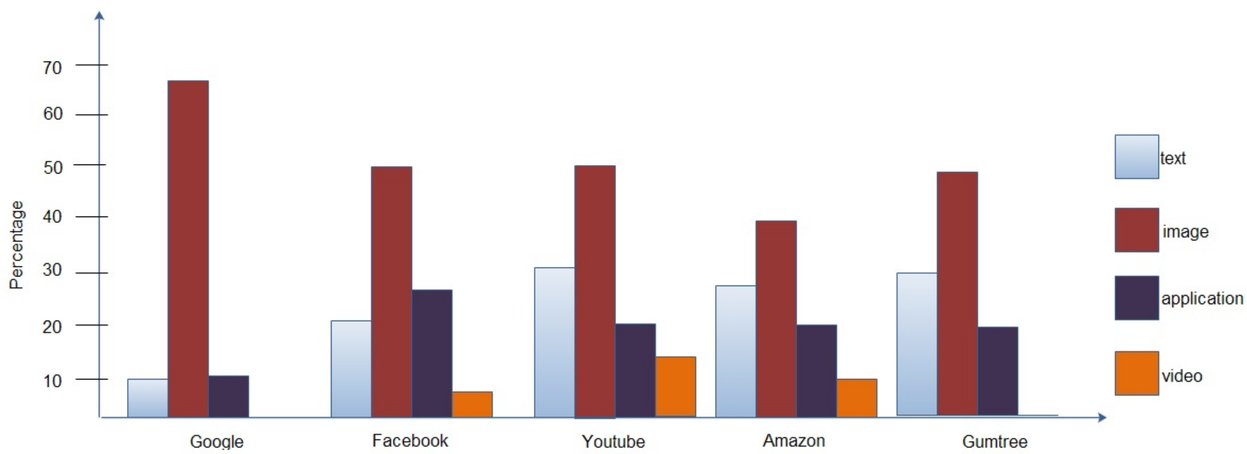

Figure 27. Bar chart showing percentage of website content

The above figures give an overall perspective of how much content is on each “homepage” of the above-mentioned websites. From these figures, it can be determined that “image” is the largest content on most of the website, followed by text, applications, and then video. This information allows for a comprehensive assessment of the performance of the networks based on each website profile type. The chart is going to be the same in comparison to the Femtocell network, as the websites have not been changed, neither will the amount of content in them.

4.4.4 Web access through HTTP assessment

The Upload/Download tests show that the downloading rate’s results are similar to the Wi-Fi and Femtocell download speed test results from the previous section. The Wi-Fi download speed can be seen to increase as the size of the downloaded becomes larger, but then download speed drops significantly when downloading the largest 200MB file. In comparison, the Femtocell download speed also increases as the file size increases, as results are relatively stable with the first 3 sets of files, (20MB, 50MB, and 100MB), but they also show a significant drop when downloading the largest 200MB file.

These results place Femtocell on the back foot as Wi-Fi outperforms Femtocells in both download speed and accessing files over the Internet, although Femtocell exhibits a bit more stability as indicated by the drop in download speed on the 200MB file which is not that much different when compared to the highest download speed result form the smaller file sizes in the Femtocell experiment. This leads to the conclusion that downloading large files are problematic for both technologies, but for smaller sized files Wi-Fi out performs Femtocell.

The major difference is in loading times between both networks in regard to accessing the Internet through HTTP. The loading time isn't related to the website having more content than the other, but by Femtocells mode of operation, as there is a longer route that the data has to follow (the mobile operator chain between the HNB and the global IP access to the server) to get to its destination, resulting in longer TCP sessions and RTT. These results are consistent with observations made in the baseline tests.

These tests lead to the conclusion that Wi-Fi's ability to access directly to the global IP network leaves Femtocells at a disadvantage again, as this operational difference is a major advantage when it comes to accessing the internet through HTTP.

4.5 Testing streaming files through RTP

In today's Internet usage, more end users want web content "on-demand". This means they want their data (in this case, video files) immediately. This leads users to stream video files instead of downloading the file and watching it later. Internet streaming capabilities utilize Real-time Transport Protocol (RTP) and Real-time Transport Control Protocol (RTCP). RTP/RTCP defines a standardized packet format for the transmission of multimedia audio and video packets over the Internet. In other words, RTP caters for applications that require a higher throughput than traditional transport protocols such as Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) can offer. While RTCP aids RTP in delivering and packaging of multimedia data by providing quality of service (QoS) feedback through statistics sent periodically to participants in a streaming multimedia session [4].

Examples of such applications are; videoconferencing applications, video on demand applications, continuous data applications, and control and measurement applications. Streaming multimedia data through both Femtocells and Wi-Fi networks are a good way to test the networks ability to handle a consistent flow of data.
Note: All testing is done in realistic conditions of scenario 2.

4.5.1 Software Used

- ISPGeeks – ISPGeeks is a free online tool used to determine accurately the streaming video quality on a network. It does this by testing TCP socket-to-socket connections for jitter. Jitter is the key performance measurement affecting real-time streaming video applications. The test accurately identifies and measures TCP delays that cause jitter and clearly shows the impact to the data flow and resulting jitter over time. ISPGeeks tests also checks network connections for video quality using RTCP and RTP over a UDP and TCP connection and analyzes the data streams for multi-media performance.

After the quality test, a performance test will be done involving videos with various resolutions from low definition 144 progressive scan (p) to 240p then 480p and finally, high definition 1080p will be analyzed on both Femtocell and Wi-Fi networks. The higher the definition the more data is sent through in order to stream the video, so in essence, this test will reveal which technology handles streaming files through RTP better.

4.5.2 ISPGeeks quality test results

Technology	Video Jitter (ms)	Video Loss (%)	Video Packet Order (%)	Left Audio Jitter (ms)	Left Audio Loss (%)	Left Audio Packet Order (%)	Right Audio Jitter (%)	Right Audio Loss (%)	Right Audio Packet Order (%)
Wi-Fi	1.63ms	0%	100%	1.4ms	0%	100%	1.44ms	0%	100%
Femtocell	2.06ms	0.16%	100%	1.18ms	0.16%	99.8%	1.26ms	0.16%	100%

Table 20. ISPGeeks quality test for Wi-Fi and Femtocell connection

Figure 28. 1080p video quality on Wi-Fi connection

Figure 29. 144p video quality on Femtocell

4.5.3 Streaming Speed test results

Video Quality	Wi-Fi Connection	Femtocell Connection
144p	5:50	5:50
240p	5:50	5:50
420p	6:59	5:59
1080p	7:30	6:30

Table 21. Wifi vs Femtocell streaming speed

4.5.4 Streaming files through RTP assessment

The ISPGeek test focused on jitter and packet loss of both networks. As mentioned in previous sections, jitter may be defined as the difference in the measure of time it takes each packet to reach its destination. In an ideal scenario, transmitted packets should take the same amount of time traveling between server and client, but as the test results show, there isn't much difference in the Wi-Fi and Femtocell jitter measurements across the board, with Wi-Fi having slightly less jitter. In regard to packet order, for both technologies, packets arrived in order, with no delays.

For the streaming speed test, a 5 minute and 50 second video was used. In an ideal scenario, the video should take exactly 5 minutes and 50 seconds to stream. But the higher the resolution the more data packets are pushed through the network. Packets do not necessarily take the same route or the same time to reach their destinations, so having excess packets on a network may lead to packets being delivered out of order resulting in delays or even discarded packets.

As results show for both networks, the higher the video resolution the longer the time taken to stream the video for both technologies. The lower resolution videos (144p and 240p) streamed the video with no packet loss or sequence errors in exactly 5 mintes and 50 seconds. As for streaming the video with much higher resolution (420p), it takes a longer time for Wi-Fi technology to stream than Femtocell.

Femtocells show little or no packet loss or sequence errors as the video streams completely in little over 5 minutes and 50 seconds. Although the video quality is better, the *buffering* time is increased significantly on the Wi-Fi tests. Buffering is the action taken by the network when there are excess packets to be sent through. These packets have to wait in a queuing area (a temporary area where data packets wait until they can be transmitted) until the network is less congested.

For the high definition (HD) 1080p video tests, there is a significant drop in performance for both technologies, but with Femtocells out performing Wi-Fi. Streaming the HD video on the Wi-Fi network revealed the longest time as the video completely stopped due to packet loss or perhaps sequence errors.

In conclusion, Femtocells outperform Wi-Fi in RTP video streaming transmissions. This is due to another operational difference that should be taken note of when choosing technologies. Femtocells utilize the High Speed Uplink Packet Access (HSUPA) scheme which allows Femtocells to fully optimize the available spread spectrum Dedicated Physical Data Channel (DPDCH) that transports RTP packets proficiently. The HSUPA mode of operation is a “connect once” scheme where once the connection is open at the beginning of the streaming session, the channel stays open and is exploited at maximum capacity. Whereas for Wi-Fi, the connection based Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme used [46]. This scheme limits Wi-Fi when it comes to RTP transmissions, as it does not dedicate resources to a specific link like Femtocells. Instead it relies on collision recovery mechanism to reduce the effect of congestion in the network.

4.6 Testing Voice Over Internet Protocol (VoIP)

Simply explained, VoIP is the process of taking analog audio signals such as voice and converting them into digital data for transmission over a packet network. This means sending voice in digital form in packets over the Internet as opposed to traditionally sending the information through circuit switched protocols like those used in Public Switched Telephone Networks (PSTN) [4].

IP networks operate on a “best effort” capacity, which means that the network does not offer any guarantees that data is delivered or that a user is given a guaranteed quality of service level. The user obtains unspecified variable bit rate and delivery time, depending on the networks current traffic load. For VoIP applications operating over the Internet, this best effort mode of operation may come as a drawback as voice messages not transmitted properly reduces the quality of the received data, making the message incoherent or garble.

The upload and download capacities of Wi-Fi and Femtocell networks come into play in regards to VoIP testing as jitter and packet loss are significant factors that can lead to poor quality in the received transmission. In other words, the faster the network, the better the VoIP quality.

4.6.1 Software Used

- VoIPspeedtester – VoIPspeedtester is an online evaluation program that measures the basic parameters (speed and quality of the high-speed Internet connection) that ensure a VoIP session.

- Myspeed.visualware.com – myspeed is another online evaluation tool that measures the parameters necessary to establish a good VoIP session, but it does this by establishing a mean opinion score (MOS) in the range of 1 – 5, where a score of 1 is considered to be extremely bad (impossible to communicate), a score of 3 is considered to be fair but with imperfections and a score of 5 is considered to be the perfect conditions for a VoIP session.

4.6.2 VoIPspeedtester tests results

Technology	Download consistency of service average (%)	Upload consistency of Service average (%)	Average Round Trip Time average (ms)	Jitter average (ms)	Packet Loss average (%)
Wi-Fi	76.4%	85.8%	152.8ms	9.16ms	0%
Femtocell	67.6%	63.6%	286.6ms	10.6ms	0%

Table 22. VoIPspeedtester average results for Wi-Fi and Femtocell connection

4.6.3 myspeed tests results

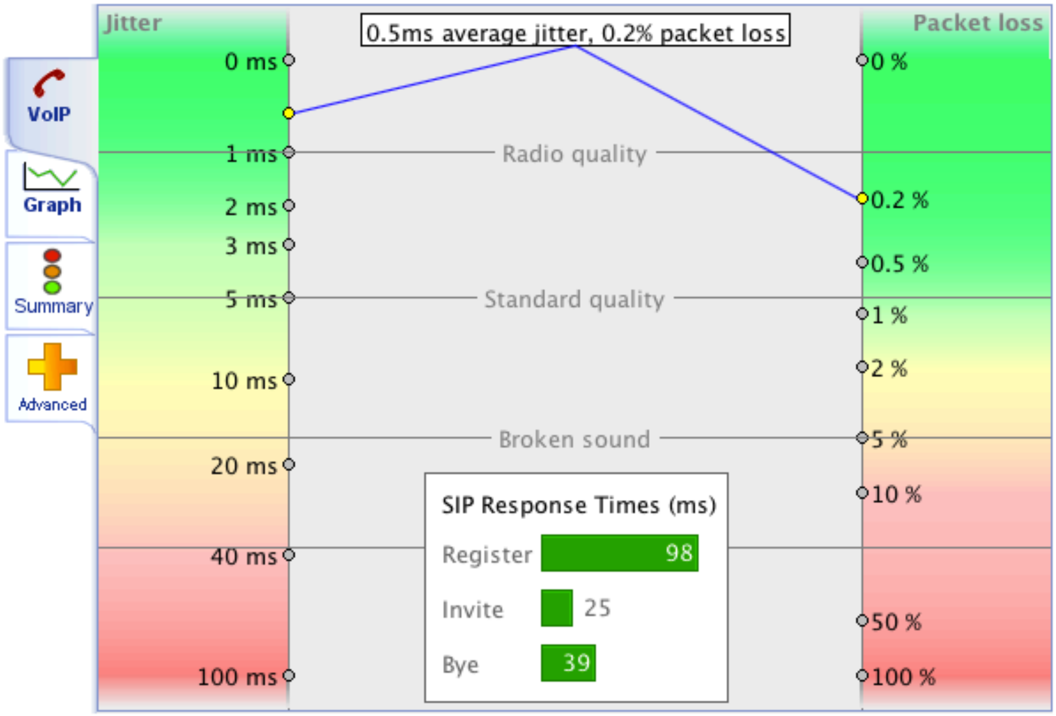

Figure 30. myspeed test for Wi-Fi connection

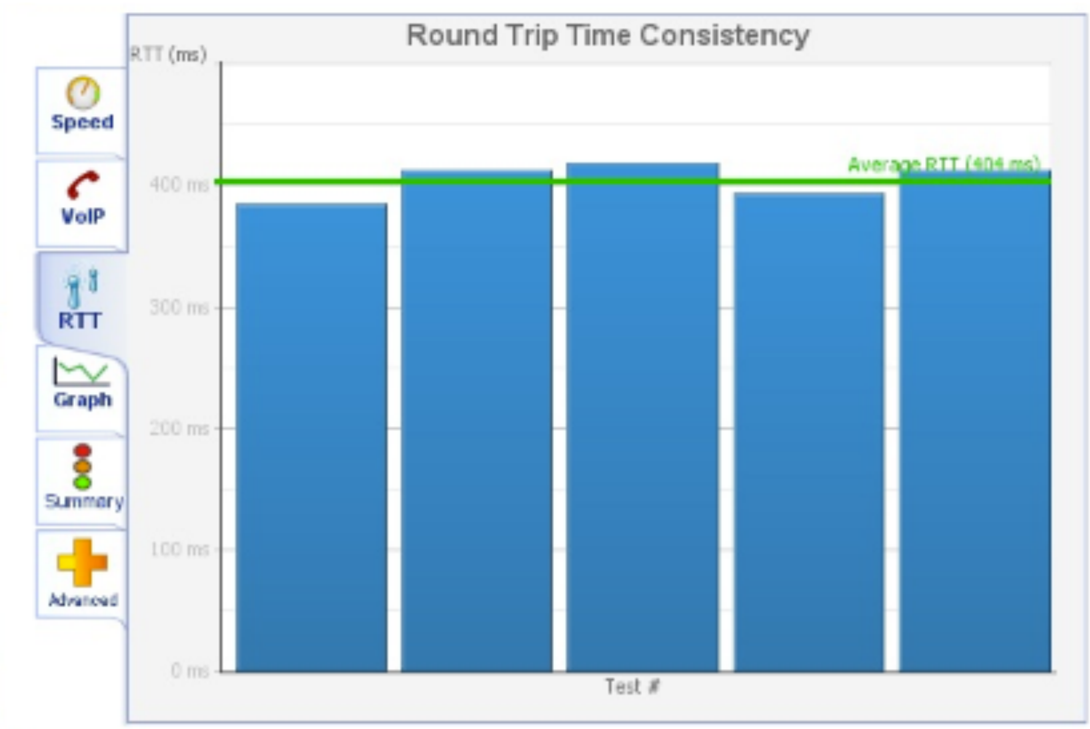

Figure 31. myspeed test for Femtocell connection

Technology	Jitter average (user to server, ms)	Jitter average (server – User), ms	Packet Loss average (User to Server, %)	Packet Loss average (server to user, %)	Mean Opinion Score (MOS)
Wi-Fi	2.9ms	9.8ms	0%	0%	4.0
Femtocell	5.1ms	23.8ms	0%	0%	3.7

Table 23. myspeed test average results for Wi-Fi and Femtocell connection

4.6.4 Voice Over Internet Protocol (VoIP) Testing Assessment

From initial baseline tests, it was established that Wi-Fi is the faster network when it comes to upload and download capacities; this is due to the packets in Wi-Fi networks having the shorter travelled route. However, realistic condition tests established that Femtocells are more robust when it comes to transmitting data with obstructing obstacles involved.

These previous test results are consistent with the VoIP test results shown in table 22, as although it is established that Wi-Fi is the faster network it does not necessarily mean it is the better network for VoIP applications. By observing the MOS in table 23, Femtocells did perform worse in comparison to the Wi-Fi network but by a slight margin. This may be explained by the fact that Wi-Fi signals are easily distorted when facing obstacles, thus reducing the received data and subsequently reducing the VoIP quality. But in comparison to Femtocells signals that are more robust when faced with obstacles, VoIP quality will not reduce as much, making both MOS results extremely close. Experimentation shows that in an ideal scenario (transmission friendly scenario), Wi-Fi will significantly outperform Femtocells. But in a realistic scenario, both technologies perform almost at the same rate due to Femtocells being able to overcome obstacles.

4.7 Conclusion

This chapter serves as an introduction into the experimentation procedures and the scenarios the experiments were conducted in. Preliminary assumptions were stated and base line testing was conducted to establish control parameters for subsequent test results.

In conclusion, it could be seen that Wi-Fi out performs Femtocells in certain areas such as upload and download speed, meaning Femtocells produce a lower data rate than Wi-Fi does for the end user.

5. Conclusions and Recommendations

5.1 Introduction

The purpose of this investigation was to accurately answer the key research question; **"Do we need Femtocells when there is Wi-Fi technology?"** To achieve this, several tests and experiments were conducted, comparing the performance and capabilities of a Femtocell enabled network to that of a traditional wireless Wi-Fi network in several use-cases, applications, and scenarios. This was done in order to better understand both technologies and how, even though they possess slightly similar architectures, have significant operational differences that should not be overlooked when choosing one technology over the other.

5.3 Key findings and conclusions

After taking an overview analysis of all results achieved, it can be said that yes Femtocells are needed but at a reduced capacity than declared by cellular service providers. Femtocells are not the silver bullet technology cellular service providers have been looking for as this investigation shows, there are inevitable drawbacks that Femtocells possess which cannot be ignored. So, in short, Femtocell networks will not readily replace Wi-Fi networks.

When initial baseline experiments were conducted, it could be seen that Wi-Fi out performs Femtocells in certain areas such as upload and download speed, meaning Femtocells produce lesser data rate than Wi-Fi does for the end user. These baseline (ideal scenario) test results were the benchmark measurements used to compare subsequent test in realistic environments.

As can be seen in the realistic scenario testing, the initial baseline test measurements changed significantly for both technologies. This is due to the mode of operation adopted by each technology, with Wi-Fi having a higher capacity channel that is shared through contention access and Femtocell having channels that are dynamically allocated in an optimal non-contended way. This means that data is transported across both networks differently. It could be argued that Femtocells could do comparatively better than Wi-Fi when their smaller channel capacity is better utilized for multiple users or difficult propagation conditions.

Obstacles and distance is a factor not to be ignored when considering which technology one should employ, as once these factors were introduced into the experimentation, it could be seen that several key performance measurements reduced for both technologies.

Upon comparing both technologies, Femtocells aren't always inferior, as the licensed spectrum it operates in is considered advantageous. This licensed spectrum guarantees a certain level of quality that can be seen in the test results in the realistic environment. But a serious disadvantage to Femtocells is the complicated process it deploys to access the Internet. As each single interaction is taken on by the Femtocell to access the global IP, it introduces more complexity as these steps in the mobile operators domain become time consuming. These complexity and time constraints will inevitably affect other performance factors, unlike Wi-Fi that connects directly to the global IP. Subsequent user application testing also revealed significant differences between technologies. Accessing the Internet through HTTP and streaming files through RTP are at two opposite extremes of the range.

HTTP testing highlights Wi-Fi's strength as it out performs Femtocells due to its larger shared channel capacity and less complex process deployed to access the global IP. On the other hand, RTP testing emphasizes Femtocells strength, as the Wi-Fi's shared channel mode of operation becomes a disadvantage to the network. RTP is essentially one-way communication with very long sequences that are sensitive to variances in packet delays. In order for optimum transmission, RTP would require a network that can transmit large files with little or no packet loss. Wi-Fi's repeated need to gain access to the shared channel leaves the network susceptible to congestion and interference from neighboring Wi-Fi access points, whereas Femtocell's optimum HSUPA features allows for dynamic resource allocation which will enhance RTP transmissions. Experiments show that Femtocells can transmit larger files than Wi-Fi, with no packet loss. These results are due to the operational differences between both technologies.

In VoIP testing, results revealed that both Wi-Fi and Femtocells performed satisfactory, with Wi-Fi slightly (but negligibly) outperforming Femtocells. The difference between both technologies in VoIP testing is in basic parameters such as one-way delay, jitter and packet loss, but the actual quality as perceived by the user is much the same for both technologies.

In summary, experimentation revealed that:

- Wi-Fi has a better data rate throughput than Femtocells in baseline tests;
- Wi-Fi signals are affected more than Femtocell signals in realistic conditions (introduction of obstacles and distance),
- Wi-Fi outperforms Femtocells in HTTP web access due to Femtocells dependency on the cellular network and the extensive and complicated process of accessing the global IP,
- Femtocells out perform Wi-Fi in RTP streaming due to Femtocells having a dynamic resource allocation mode of operation; and lastly
- VoIP testing revealed both networks to be similar in quality of received VoIP transmissions with Wi-Fi slightly (buy negligibly) outperforming Femtocells.
- No, Femtocells should not replace current Wi-Fi technology as Wi-Fi is a viable solution to wireless indoor communications
- Although Femtocells may not be the silver bullet solution mobile operators are looking for in today's industry, other small cell solutions like Picocells and

microcells are relevant as they possess a wider range and may be used in larger areas as they can hold more users on the network.

5.1 Recommendations and future work

These results show that neither technology is better than the other if placed in a busy realistic environment. Each area of testing was selected because it shows the everyday usage of Internet traffic. Perhaps instead of looking at these technologies as competing entities, they could be regarded as complementary entities. Employing both technologies in a Small-Office, Home-Office (SOHO) environment could prove fruitful as each technology could support the other in areas of shortcomings. As Wi-Fi networks become congested, performance will continue to degrade due to the fact that 802.11 standards do not support coordination across different access points. Having Femtocells integrated with Wi-Fi will increase the end user QoE as the reliability expected from a wired broadband network will could be incorporated in the mobile broadband experience.

Femtocells will not replace Wi-Fi because Wi-Fi is still a strong solution to end users data traffic needs. Femtocells represent only a very small fraction of the overall cellular market with estimations of just below 49 million Femtocell access points in the market by 2014 and 114 million mobile users accessing mobile networks through Femtocells during that year. Whether Femtocells can ever play a dominant role in the network itself depends not only on the technical challenges discussed above but on a number of factors based on regulatory, economic and market considerations.

When it comes to regulations governing Femtocell usage in South Africa, ICASA should consider the fact that with Femtocells, the licensed operator providing the services maintains control. Femtocells only operate within parameters set by the operator. Although Femtocells have a high degree of intelligence to automatically ensure that they operate at power levels and frequencies that are unlikely to create interference, operators always set the limits on these parameters, not the end user. The operator is always able to create or deny service to individual Femtocells or users. This control is maintained whether the operator or the end-user owns the Femtocell. Developing new regulations to cater for Femtocell usage in the country will be beneficial to both service providers and end-users alike.

The combination of both technologies could be an interesting area for future work, using a converged gateway architecture that combines Wi-Fi and LTE Femtocells could demonstrate how combining the technologies will allow end users take advantage of both forms of connectivity to further enhance data throughput and overall reliability.

References

[1] "**Wi-Fi Alliance** (2013). Organization Official industry association website. *www.wi-fi.org.* [Online] Wi-Fi Alliance website, 2013 [last Cited: 25th July 2013.] Retrieved from http://www.wi-fi.org/discover-and-learn

[2] **Traci Terluinm** (2000). IEEE 802.11 *wireless LAN Technical Paper, wireless Freedom at Ethernet speeds, 3Com Technical Paper*, pg. 1 – 13, [last Cited: 25th July 2013.] Retrieved from
http://www.cs.colorado.edu/~rhan/CSCI_7143_001_Fall_2002/Papers/IEEE_802_11b.pdf

[3] **LAN MAN Standards Committee of the IEEE Computer Society** (1999). *ANSI/IEEE Std 802.11, 1999 Edition (ISO/IEC 8802-11:1999) Local and metropolitan area networks—Specific Requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, pg. v – vi, [last Cited: 25th July 2013.] Retrieved from http://pdos.csail.mit.edu/decouto/papers/802.11.pdf

[4] **James F. Kurose and Keith W. Ross** (2012*). Computer Networking: A Top-Down Approach (5th Edition)*, pg. 553 – 622. ISBN-10: 0132856204 | ISBN-13: 978-0132856201

[5] **Cory Jensson** (2013). The Farlex free Encyclopedia. *www.thefreedictionary.com* [online] the free dictionary by Farlex, 2013 [last cited: 26th July 2013]. Retrieved from: http://encyclopedia2.thefreedictionary.com/distributed+systems

[6] **IEEE Standards Association** (2009) 802.11n-2009 - *IEEE Standard for Information technology-- Local and metropolitan area networks-- Specific requirements-- Part 11: Wireless LAN Medium Access Control (MAC)and Physical Layer (PHY) Specifications Amendment 5: Enhancements for Higher Throughput.* [last Cited: 26th July 2013]. Retrieved from: http://standards.ieee.org/findstds/interps/802.11n-2009.html

[7] **Alternative wireless** (2013). *5 GHz vs 2.4 GHz Wireless Networks* www.alternativewireless.com [online]. Alternative wireless blog, 2013. [Last Cited: 26th July 2013]. Retrieved from: http://www.alternativewireless.com/cellular-antennas/wifi-solutions/5ghz-wireless-lan.html

[8] **John Donovan** (2013). *Is 5 GHz the Promised Land for Embedded Wireless Applications?* Low-Power Design for Convergence Promotions LLC. www.digikey.com [Online]. Web Article [Last Cited 26th July 2013]. Retrieved from: http://www.digikey.ca/ca/en/techzone/wireless/resources/articles/is-5-ghz-the-promised-land-embedded-wireless.html

[9] **Nigerian Communications Commission - NCC** (2004). *Regulatory Guidelines for the use of 2.4GHz ISM band for commercial Telecoms services* [Online]. Legal Guideleines and Regulations for deployment of Wi-Fi. [Latst Cited: 29th July 2013]

[10] **QUALCOMM White paper** (2011), *A Comparison of LTE Advanced HetNets and Wi-Fi.* A research comparison of lte advances hetnets and wifi. [October 2011]

[11] **Hanrahan Hu** (2007). *Network convergence : services, applications, transport, and operations support*. ISBN: 0470024410 ,9780470024416 (cloth: alk. paper)

[12] **Jinyuan Zhang and Ivan Stojmenovic** (July 2005), *Cellular Networks.* University of Alabama, University of Ottawa, Canada

[13] **Tinnirello Ilenia, Bianchi Giuseppe**. *Wireless Networks. Wireless Networks*. [Online] University of Parlemo, 2005. [Last Cited: 29th July 2013.] Retrieved from: http://www.tti.unipa.it/~ilenia/course/00-intro.pdf.

[14] **Pashtan, Ariel**. Retrieved from:
http://www.awarenetworks.com/publications/6.108.10.CellularTelephony.pdf.
http://www.awarenetworks.com/publications/6.108.10.CellularTelephony.pdf. [Online] 2006. [Cited: 29th July 2013.]
http://www.awarenetworks.com/publications/6.108.10.CellularTelephony.pdf.

[15] **3GPP**. *LTE; GPRS Enhancements for EUTRAN Access*. Sophia Antapolis : ETSI, 2010. TS 23.401 version 9.6.0 Release 9.

[16] **Dalman Erik, Parkval Stefan, Skold Johan, Beming Per**. *3G Evolution: HSPA and LTE for Mobile Broadband*. s.l. : Academic Press, Elsevier Ltd., 2008. 978-0-12-374538-5.

[17] **ITU-R.** *ITU global standard for international mobile telecommunications´IMT-Advanced´.* Radio Communication Sector ITU-R. [Online] ITU, 7 October 2010. [Last Cited: 29th July 2013.] Retrieved From: http://www.itu.int/ITU-R/index.asp?category=information&rlink=imt-advanced&lang=en.

[18] **ITU/BDT**. *ITU/BDT Arab Regional Workshop on 4G Wireless Systems:. Evolution path towards 4G.* [Online] ITU/BDT, 29 January 2010. [Last Cited: 29th July 2013.] Retrieved from http://www.itu.int/ITU- D/arb/COE/2010/4G/Documents/Doc2-LTE%20Workshop_TUN_Session1_Evolution%20path%20towards%204G.pdf.

[19] **David Goldman** (December 2010). *4G is a myth (and a confusing mess).* [Online article] www.cnnmoney.com [Last Cited: 29th July 2013] Retrieved from: http://money.cnn.com/2010/12/01/technology/4g_myth/index.htm

[20] **Csamii**. (March 2011) *Introducing LTE-Advanced.* [Online Article]. www.agilent.com

www.agilent.com/find/4glte. Retrieved from:
http://cp.literature.agilent.com/litweb/pdf/5990-6706EN.pdf. [Last Cited: 29th July 2013]

[21] **Smart communications Inc**. [online] http://www1.smart.com.ph/corporate Retrieved from: http://www1.smart.com.ph/bro/lte/ [Last Cited: 29th July 2013]

[22] **Cisco Visual Networking Index** (2012): *Global Mobile Data Traffic Forecast Update, 2012–2017.*
Retrieved from:
http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-520862.html

[23] **Syed Faraz Hasan, Nazmul Haq Siddique and Shyam Chakraborty**, (2009.) "*Femtocell versus WiFi – A Survey and Comparison of Architecture and Performance".* Ulster University, intelligent systems research center faraz_hasan-s@email.ulster.ac.uk, {nh.siddique, ss.chakraborty}@ulster.ac.uk

[24] **ITU Radio communication Bureau (BR**).(2003) *RECOMMENDATION ITU-R M.1036-2 - Frequency arrangements for implementation of the terrestrial component of International Mobile Telecommunications-2000 (IMT-2000) in the bands* 806-960 MHz**, 1 710-2 025 MHz, 2 110-2 200 MHz and 2 500-2 690 MHz.* ITU-R 229/8

[25] **The small cell Forum** (March 2011). Femto forum official website. Retrieved from: http://www.smallcellforum.org/aboutsmallcells-small-cells-what-is-a-small-cell [Last cited: 29th July 2013)

[26] **Qualcomm** (2013). *Small Cells Bringing Network Closer to User.* Retrieved from: *http://www.qualcomm.com/solutions/wireless-networks/technologies/smallcells [Last cited: 29th July 2013]*

[27] **Zahid Ghadialy,** "How Wi-Fi and Femtocells complement one another to optimise coverage and capacity" 2012. Retrieved from: http://www.slideshare.net/zahidtg/how-wifi-and-femtocells-complement-one-another-to-optimise-coverage-and-capacity

[28] **Airvana** (2013). *Femtocell Netwrok Architecture*. www.airvana.com [Online] Retrieved from: http://www.airvana.com/technology/femtocell-network-architecture/#Common_Elements_of_the_Femtocell_Network_Architecture. [Last Cited: 29th July 2013]

[29] **Silventoinen M.I. et al**, 1996. "*Analysis of a New Channel Access Method for Home Base Station*," Proceedings of 5th IEEE International Conference on Universal Personal Communications (ICUPC). Cambridge, MA,USA, pp. 930-935

[30] **Jeffrey G. Andrews, Holger Claussen, Mischa Dohler, Sundeep Rangan, Mark C. Reed** (2012) *"Femtocells: Past, Present, and Future"*

[31] **S. Carlow and C. Wheelock**, (2007) "*Femtocell market challenges and opportunities,*" ABI Research Report.

[32] **3GPP**. (2011). "*3G Home NodeB Study Item Technical Report*," TR 25.820 (release 11)

[33] **Harish Viswanathan and Alexander Stolyar,** (May 2010). *Interference Management in Femto/Small Cell and Macro Environments.* Alcatel.Lucent white paper.

[34] **Uday Sankar,** *Femtocell*. Performance analusis lab, IISc, Bangalore. Retrieved from: pal.ece.iisc.ernet.in/PAL/presentations/Uday_FemtoCells.pptx [Last cited: 31st July 2013]

[35] **S. Feng and E. Seidel**, (May 2010) “Self-Organizing Networks (SON) in 3GPP Long Term Evolution,” *NOMOR whitepaper*

[36] **G. Boudreau, J. Panicker, N. Guo, R. Chang, N. Wang, and S. Vrzic**, “Interference Coordination and Cancellation for 4G Networks,” *IEEE Comm. Mag.,* vol. 47, no. 4, pp. 74–81, Apr. 2009.

[37] **The small cell Forum**, (march 2011) “Regulatory Aspects of Femtocells - Second Edition,” Retrieved from: http://www.smallcellforum.org/Files/File/024_FF_Regulatory_Aspects_of_Femtocells_Ed2_0311.pdf. [Last Cited 31st July 2013)

[38] **Barlow Keener**, “*Femtocell Regulatory and Legal issues*”. Keener Law Group. Retrieved from: http://www.slideshare.net/alwaysoncarl/lesliebill/ [Last cited: 31st Julu, 2013]

[39] **Anton Okmyanskiy** (August 2009).”Cisco *Service Provider Mobility: Wi-Fi vs Femtocell”*. Retrieved from: http://www.slideshare.net/CiscoMobilityCommunity/wifi-vs-femtocell [Last Cited: 31st July 2013]

[40] **Mostafa Zaman Chowdhury, Yeong Min Jang and Zygmunt J. Haas** (August 2010), International Journal of Wireless & Mobile Networks (IJWMN), Vol.2, No.3 *“Network Evolution and QoS provisioning for Integrated Femtocell/Macrocell Networks”*

[41] **Mostafa Zaman Chowdhury** and **Yeong Min Jang** (January 2013) EURASIP Journal on Wireless Communications and Networking, “*Handover management in high-dense femtocellular networks”* doi:10.1186/1687-1499-2013-6. Onlinve version of article can

be retrieved from: http://jwcn.eurasipjournals.com/content/2013/1/6 [Last Cited: 31st July 2013]

[42] **V. Chandrasekhar, J. G. Andrews, and A. Gatherer**,(Sept. 2008) "Femtocell Networks: A Survey," IEEE Commun. Magazine

[43] **Ivan Poole**. "*Femtocell Security*" Radio-Electronics.com [Online Article] Retrieved from: http://www.radio-electronics.com/info/cellulartelecomms/femtocells/femto-cells-security.php, [Last Cited: 31st July 2013]

[44] **EBU Technology and Development**, (2011). "*Report on the Future of Terrestrial Broadcasting*" EBU.UER Technical report 013, white paper. Online version of article can be retrieved from: https://tech.ebu.ch/docs/techreports/tr013.pdf [Last Cited: 31st July 2013]

[45] **IT-Online** (July 2013) "*WiFi could answer broadband challenges"*

[46] **Kathryn Vercillio**,(2008) "*A Beginner's Guide to Femtocell Technology*"

[47] **Rashid A. Saeed, Mohammad Hasan, Rania A. Mokhtar** "*The Comparison between WLAN and Femtocell*" Sudan University of Science and Technology, Sudan

[48] **Guillem Femenias, Nadal Felip Riera Palou.** "*Interference management in femtocell-aided cellular networks*". Universitat de les Illes Balears, department of mobile communications

[49] **Syed Faraz Hasan, Nazmul Haq Siddique and Shyam Chakraborty**, (2009). "*Femtocell versus WiFi – A Survey and Comparison of Architecture and Performance*". Ulster University, intelligent systems research center

[50] **Andrei Gurtov, Rashid A. Saeed** "*Femtocell Communications and Technologies : Business Opportunities and Deployment Challenges*" (2012, Hardcover)
ISBN-10: 1466600926 | ISBN-13: 9781466600928

[51] **Jie Zhang, Guillaume de la Roche**. "*Femtocells: Technologies and Deployment*"

[52] **DR. IR. Joko Suryana**,(2011)"*mobile data offloading: femtocells vs wifi*". institute of technology Bandung, laboratory of radio telecommunications and microwaves

[52] **DR. IR. Joko Suryana**,(2011)"*mobile data offloading: femtocells vs wifi*". institute of technology Bandung, laboratory of radio telecommunications and microwaves

[53] **Cisco Systems,** (2004). *"solutions for mobile network Opertors"*. White paper, retrieved from: http://www.cisco.com/en/US/solutions/collateral/ns341/ns523/ns177/net_implementation_white_paper09186a00801fc7fa.pdf [last Cited: August 12, 2013]

[54] **Infonetics**, (March 2012). "small cell equipment market size and forcast report. [Online] retrieved from; http://www.infonetics.com/pr/2012/2H11-Small-Cell-Equipment-Market-Highlights.asp [last cited: August 12, 2013]

[55] **Mostafa Zaman Chowdhury, Yeong Min Jang, and Zygmunt J. Haas**, "Network Evolution and QoS Provisioning for Integrated Femtocell/Macrocell Networks," International Journal of Wireless & Mobile Networks (IJWMN), August 2010.

[56] **Ronny Yongho Kim, Jin Sam Kwak, and Kamran Etemad**, "WiMAX Femtocell: Requirements, Challenges, and Solutions," IEEE Communication Magazine, September 2009

[57] **Chunlei Yin, Guangjun Wen, Zhengyong Feng,** (2010). "*Simulation Research of 802.11n Channel Model D in NS2*". Published in Computer Science and Information Technology (ICCSIT), 2010 3rd IEEE conference. DOI: 10.1109/ICCSIT.2010.5564817

[58] **Bradley Mitchell** (2013). "*What is a computer ping test?*". About.com [Online Article] Retrieved from: http://compnetworking.about.com/od/homenetworktroubleshooting/f/pingtest.htm Last cited: 22nd August 22, 2013

[59] **David W. Snow** (February 2013). "*Testing your internet Speed, packet loss, jitter and latency"* [online article] Retrieved from: http://www.agingsafely.com/blogs/articletype/articleview/articleid/102/testing-your-internet-speed-packet-loss-jitter-and-latency.aspx. Last cited: August 22 2013

[60] **James K. Bare** (September 2012). "*The comparison of performance and capabilities of femtocells vs Wi-Fi networks".* The Naval Postgraduate School, Monterey California

Appendix A

Appendix A through M shows the test results for the experimentations conducted.

Results for speed.net tests

Test #	Ping (ms)	Downloads peed (Mb/s)	Upload speed (Mb/s)
1	24	19.11	4.10
2	25	19.24	4.20
3	24	19.14	4.11
4	25	19.27	4.20
5	25	22.16	4.20
6	25	22.74	4.50
Average	24.6ms	20.27mb/s	4.18mb/s

Table 24. Wi-Fi speedtest.net connection results

Test #	Ping (ms)	Downloads peed (Mb/s)	Upload speed (Mb/s)
1	53	10.21	0.33
2	42	11.85	0.33
3	54	10.80	0.41
4	52	9.63	1.12
5	44	11.44	0.31
6	44	12.80	0.33
Average	48.1ms	11.12mb/s	0.47mb/s

Table 25. Femtocell speedtest.net connection results

Appendix B

Results for ping-test.net tests

Test #	Download speed (Mb/s)	Upload Speed (Mb/s)	Ping: Large packets (ms)	Ping: small packets (ms)	Average Latency (ms)
1	2.9	0.84	296	674	485
2	3.2	0.89	290	675	490
3	2.7	0.92	295	680	475
4	2.6	0.82	293	695	488
5	3.0	0.88	296	688	478
6	3.0	0.88	296	688	478
Average	2.9mb/s	0.87mb/s	294.33ms	683ms	482ms

Table 26. Wi-Fi Ping-test.net connection results

Test #	Download speed (Mb/s)	Upload Speed (Mb/s)	Ping: Large packets (ms)	Ping: small packets (ms)	Average Latency (ms)
1	1.8	0.16	153	98	125
2	1.5	0.05	151	87	199
3	1.9	0.75	145	82	114
4	2.0	0.14	181	93	137
5	1.6	0.19	193	86	139
6	1.8	0.48	160	90	145
Average	1.7mb/s	0.29mb/s	163.83ms	89.3ms	143.1ms

Table 27. Femtocell ping-test.net connection results

Appendix C

Results for Pingtest.net Tests

Test #	Packet loss (%)	Ping (ms)	Jitter (ms)	Score (/5)
1	0	23	6	4.3
2	0	36	10	4.3
3	0	33	7	4.3
4	0	26	12	4.3
5	0	24	11	4.3
6	0	27	2	4.3
Average	0%	28.1ms	8ms	4.3

Table 28. Wi-Fi Pingtest.net connection results

Test #	Packet loss (%)	Ping (ms)	Jitter (ms)	Score (/5)
1	0	51	21	3.3
2	0	44	6	3.3
3	0	50	13	3.4
4	0	47	14	3.3
5	0	49	10	3.3
6	0	51	13	3.2
Average	0	48.6ms	12.8ms	3.3

Table 29. Femtocell pingtest.net connection results

Appendix D

Results for Scenario 1 speedtest.net test

Test #	Ping (ms)	Download speed (Mb/s)	Upload speed (Mb\s)
1	20	12.50	7.31
2	25	13.86	8.20
3	25	13.00	8.12
4	25	10.68	7.45
5	20	13.96	7.90
6	25	11.10	8.00
Average	23.33ms	12.51mb/s	7.83mb/s

Table 30. Scenario 1 Wi-Fi speedtest.net connection results

Test #	Ping (ms)	Download speed (Mb/s)	Upload speed (Mb\s)
1	133	6.55	0.99
2	146	6.40	1.05
3	150	6.45	1.00
4	159	6.54	1.04
5	159	6.33	0.95
6	154	6.52	0.89
Average	150ms	6.45mb/s	0.96mb/s

Table 31. Scenario 1 Femtocell speedtest.net connection result

Appendix E

Results for Scenario 2 speedtest.net Tests

Test #	Ping (ms)	Download speed (Mb/s)	Upload speed (Mb\s)
1	25	15.53	3.55
2	46	16.27	6.81
3	55	14.95	3.15
4	25	17.75	3.85
5	25	18.27	4.00
6	15	18.55	4.05
Average	31.8ms	16.88mb/s	4.29mb/s

Table 32. Scenario 2 Wi-Fi speedtest.net connection results

Test #	Ping (ms)	Download speed (Mb/s)	Upload speed (Mb\s)
1	1003	15.45	1.45
2	845	10.23	0.95
3	450	13.85	1.05
4	639	12.37	1.10
5	150	7.99	1.15
6	385	11.67	0.77
Average	578.6ms	11.92mb/s	1.07mb/s

Table 33. Scenario 2 Femtocell speedtest.net connection results

Appendix F

Results for Scenario 3 Speeptest.net tests

Test #	Ping (ms)	Download speed (Mb/s)	Upload speed (Mb\s)
1	25	15.45	4.02
2	25	12.87	3.55
3	25	13.07	3.75
4	25	15.20	3.80
5	25	14.45	3.45
6	25	11.50	3.86
Average	25ms	13.75mb/s	3.73mb/s

Table 34. Scenario 3 Wi-Fi speedtest.net connection results

Test #	Ping (ms)	Downloads peed (Mb/s)	Upload speed (Mb\s)
1	510	15.50	0.57
2	609	9.55	0.64
3	658	10.75	1.50
4	747	7.82	1.10
5	373	13.30	1.35
6	450	11.57	0.90
Average	557ms	11.42mb/s	1.01mb/s

Table 35. Scenario 3 Femtocell speedtest.net connection results

Appendix G

Results for Scenario 4 speedtest.net Tests

Test #	Ping (ms)	Downloads peed (Mb/s)	Upload speed (Mb\s)
1	25	8.90	4.07
2	25	9.00	3.97
3	25	8.46	8.85
4	25	10.05	3.45
5	25	8.48	3.95
6	25	11.97	4.20
Average	25ms	9.47mb/s	4.74mb/s

Table 36. Scenario 4 Wi-Fi speedtest.net connection results

Test #	Ping (ms)	Downloads peed (Mb/s)	Upload speed (Mb\s)
1	378	5.50	0.50
2	327	4.80	0.65
3	345	3.99	0.52
4	259	5.20	0.49
5	350	4.40	0.43
6	377	3.95	0.51
Average	339.33ms	4.64mb/s	0.51mb/s

Table 37. Scenario 4 Femtocell speedtest.net connection results

Appendix H

Results for Downtester.net 20MB file

Test #	Speed (Kbytes/s)	Speed (Mbits/s)
1	850.0	7.95
2	880.5	7.80
3	950.7	6.96
4	961.5	7.85
5	875.5	8.00
6	895.9	7.65
Average	902.35kb/s	7.70mbps

Table 38. Wi-Fi connection results 20MB file

Test #	Speed (Kbytes/s)	Speed (Mbits/s)
1	450	4.00
2	475	3.90
3	480	3.85
4	510	4.10
5	490	4.24
6	483	4.05
Average	481.33kb/s	4.02mbps

Table 39. Femtocell connection results 20MB file

Appendix I

Results for Downtester.net 50MB file

Test #	Speed (Kbytes/s)	Speed (Mbits/s)
1	1005.5	8.50
2	980.9	7.65
3	985.0	7.90
4	959.5	7.70
5	995.0	8.63
6	1000.9	8.90
Average	987kb/s	8.2mbps

Table 40. Wi-Fi connection results 50MB file

Test #	Speed (Kbytes/s)	Speed (Mbits/s)
1	525.0	4.50
2	530.5	4.18
3	551.9	4.90
4	527.4	4.75
5	578.2	4.80
6	510.7	4.83
Average	537kb/s	4.6mbps

Table 41. Femtocell connection result 50MB file

Appendix J

Results for Downtester.net 100MB file

Test #	Speed (Kbytes/s)	Speed (Mbits/s)
1	1025.4	7.52
2	980.1	7.90
3	950.7	8.20
4	995.2	8.10
5	957.5	7.95
6	989.9	7.72
Average	984.3kb/s	7.89mbps

Table 42. Wi-Fi connection result 100MB file

Test #	Speed (Kbytes/s)	Speed (Mbits/s)
1	489.9	5.01
2	520.5	4.59
3	518.7	4.95
4	490.0	4.65
5	515.7	4.89
6	499.9	4.95
Average	505.78kb/s	4.84mbps

Table 43. Femtocell connection result 100MB file

Appendix K

Results for Downtester.net 200MB file

Test #	Speed (Kbytes/s)	Speed (Mbits/s)
1	410.5	4.40
2	395.9	3.95
3	390.5	3.30
4	400.9	3.45
5	411.0	3.90
6	399.5	4.00
Average	401.38kb/s	3.83mbps

Table 44. Wi-Fi connection result 200MB file

Test #	Speed (Kbytes/s)	Speed (Mbits/s)
1	250.5	1.90
2	226.7	1.85
3	225.9	1.77
4	218.7	1.60
5	235.8	1.59
6	227.3	1.89
Average	230.8kb/s	1.76mbps

Table 45. Femtocell connection result 200MB file

Appendix L

Results for ISPGeeks quality test

Test #	Video Jitter (ms)	Video Loss (%)	Video Packet Order (%)	Left Audio Jitter (ms)	Left Audio Loss (%)	Left Audio Packet Order (%)	Right Audio Jitter (%)	Right Audio Loss (%)	Right Audio Packet Order (%)
1	1.5	0	100	0.7	0	100	3.3	0	100
2	3.2	0	100	1.2	0	100	0.7	0	100
3	1.6	0	100	3.2	0	100	1.2	0	100
4	1.8	0	100	0.7	0	100	0.6	0	100
5	1.7	0	100	1.3	0	100	1.4	0	100
Average	1.63ms	0%	100%	1.4ms	0%	100%	1.44ms	0%	100%

Table 46. ISPGeeks quality test results for Wi-Fi connection

Test #	Video Jitter (ms)	Video Loss (%)	Video Packet Order (%)	Left Audio Jitter (ms)	Left Audio Loss (%)	Left Audio Packet Order (%)	Right Audio Jitter (%)	Right Audio Loss (%)	Right Audio Packet Order (%)
1	3.9	0	100	2.0	0	100	1.1	0	100
2	2.3	0	100	1.0	0	100	1.0	0	100
3	1.4	0	100	1.0	0	100	1.0	0	100
4	1.3	0.8	100	0.9	0	100	2.3	0	100
5	1.4	0	100	1.0	0.8	99	0.9	0.8	100
Average	2.06ms	0.16%	100%	1.18ms	0.16%	99.8%	1.26ms	0.16%	100%

Table 47. ISPGeeks quality test for Femtocell connection

Appendix M

Results of VoIPspeedtester tests

Test #	Download consistency of service (%)	Upload consistency of Service (%)	Average Round Trip Time (ms)	Jitter (ms)	Packet Loss (%)
1	80	88	158	8.0	0
2	90	86	146	10.3	0
3	80	87	157	10.9	0
4	60	76	149	8.6	0
5	72	92	154	8.0	0
Average	76.4%	85.8%	152.8ms	9.16ms	0%

Table 48. VoIPspeedtester results for Wi-Fi connection

Test #	Download consistency of service (%)	Upload consistency of Service (%)	Average Round Trip Time (ms)	Jitter (ms)	Packet Loss (%)
1	77	57	293	11	0
2	65	56	289	12	0
3	61	67	282	8	0
4	69	70	288	10	0
5	66	68	281	12	0
Average	67.6%	63.6%	235.8ms	10.6ms	0%

Table 49. VoIPspeedtester results for Femtocell connection

Appendix N

Results for MYspeed tests

Test #	Jitter (user to server, ms)	Jitter (server – User), ms	Packet Loss (User to Server, %)	Packet Loss (server to user, %)	Mean Opinion Score (MOS)
1	2.9	10.2	0	0	4.1
2	3.0	9.5	0	0	4.1
3	3.4	9.7	0	0	4.0
4	2.7	9.7	0	0	3.9
5	2.9	9.9	0	0	4.0
Average	2.9ms	9.8ms	0%	0%	4.0

Table 50. Myspeed test results for Wi-Fi connection

Test #	Jitter (user to server, ms)	Jitter (server – User), ms	Packet Loss (User to Server, %)	Packet Loss (server to user, %)	Mean Opinion Score (MOS)
1	4.5	22.5	0	0	3.7
2	5.4	24.7	0	0	3.5
3	6.0	23.9	0	0	3.7
4	5.5	24.0	0	0	4.0
5	4.5	24.2	0	0	3.7
Average	5.1ms	23.8ms	0%	0%	3.7

Table 51. Myspeed test results for Femtocell connection