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ENABLING SMART CITY SERVICES FOR HETEROGENEOUS WIRELESS NETWORKS

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This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science in Electrical Engineering

Under the Supervision of Dr. Atef Amin Abdrabou

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Declaration of Original Work

I, Besintha Jafar Marakkarakath, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*Enabling Smart City Services for Heterogeneous Wireless Networks*", hereby, solemnly declare that this thesis is my own original research work that has been done and prepared by me under the supervision of Dr. Atef Abdrabou, in the College of Engineering at UAEU. This work has not previously been presented or published, or formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation, and/or publication of this thesis.

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Abstract

A city can be transformed into a smart city if there is a resource-rich and reliable communication infrastructure available. Smart city in effect improves the quality of life of citizens by providing the means to convert the existing solutions to smart ones. Thus, there is a need for finding the suitable network structure that is capable of providing sufficient capacity and satisfactory quality-of-service in terms of latency and reliability. In this thesis, we propose a wireless network structure for smart cities. Our proposed network provides two wireless interfaces for each smart city node. One is supposed to connect to a public WiFi network, while the other is connected to a cellular network (such as LTE). Indeed, Multi-homing helps different applications to use the two interfaces simultaneously as well as providing the necessary redundancy in case the connection of one interface is lost. The performance of our proposed network structure is investigated using comprehensive ns-2 computer simulations. In this study, high data rate real-time and low data rate non-real time applications are considered. The effect of a wide range of network parameters is tested such as the WiFi transmission rate, LTE transmission rate, the number of real-time and non-real time nodes, application traffic rate, and different wireless propagation models. We focus critical quality-of-service (QoS) parameters such as packet delivery delay and packet loss. We also measured the energy consumed in packet transmission. Compared with a single-interface WiFi-based or an LTE-based network, our simulation results show the superiority of the proposed network structure in satisfying QoS with a lower latency and lower packet loss. We found also that the proposed multi homing structure enables the smart city sensors and other applications to realize a greener communication by consuming lesser amount of transmission power rather than single interface-based networks.

Keywords: Smart city, multi-homing, packet delay, packet loss, WiFi, LTE, quality of service, energy efficient.

Title and Abstract (in Arabic)

تمكين خدمات المدن الذكية للشبكات اللاسلكية غير المتجانسة

الملخص

يمكن تحويل المدينة إلى مدينة ذكية إذا كان هناك بنية تحتية للاتصالات موثوقة و غنية بالموارد اللازمة بها المتاحة. المدينة الذكية تحسن جودة و طبيعة حياة السكان من خلال توفير وسائل لتحويل الخدمات القائمة إلى الخدمات الذكية. وبالتالي، هناك حاجة إلى إيجاد بنية شبكة مناسبة قادرة على توفير قدرة استيعابية كافية وجودة مرضية من الخدمة من ناحيتي سرعة الاستجابة والموثوقية. في هذه الرسالة، نقترح بنية شبكة لاسلكية للمدن الذكية. توفر شبكتنا المقترحة واجهات لاسلكية لكل عقدة داخل المدينة الذكية. يمكن ذلك عن طريق الاتصال بشبكة واي فاي العامة أو الاتصال بالشبكة الخلوية (مثال LTE). في الواقع، تساعد الشبكة المقترحة في استخدام تطبيقات الطريقتين (الواجهتين) في وقت واحد، فضلا عن توفير التكرار اللازم في حالة فقدان الاتصال بواجهة واحدة. ويتم التحقيق تلك الخدمة عن طرق بناء هيكل الشبكة المقترحة باستخدام محاكاة حاسوبية (ns-2) شاملة .في هذه الدراسة، يتم النظر في معدل البيانات العالية في الوقت الحقيقي معدل البيانات المنخفضة في الوقت الغير الحقيقي. يتم اختبار تأثير مجموعة واسعة من مدخلات الشبكة مثل معدل انتقال الواي فاي، ومعدل انتقال ال LTE، وعدد عقد كل من الوقت الحقيقي و الوقت الغير الحقيقي، ومعدل حركة التطبيق، ونماذج انتشار لاسلكية مختلفة. ونركز في هذا البحث على مدخلات نوعية الخدمة الهامة مثل تأخير تسليم مجموعة الرسائل وفقدان مجموعة الرسائل. وقسنا أيضا الطاقة المستهلكة في نقل مجموعة الرسائل. وبالمقارنة مع شبكة واي-في ذات واجهة واحدة أو شبكة قائمة على (LTE)، تُظهر نتائج المحاكاة لدينا تفوق بنية الشبكة المقترحة في تلبية جودة الخدمة مع زمن استجابة أقل وفقدان أقل مجموعة الرسائل. لقد وجدنا أيضا أن الهيكل المقترح يوفر استخدام أجهزة الاستشعار للمدينة الذكية وغيرها من التطبيقات لتحقيق اتصالات أكثر صداقة للبيئة من خلال استهلاك كمية أقل من قوة الإرسال بدلا من الشبكات القائمة على واجهة واحدة.

مفاهيم البحث الرئيسية: المدينة الذكية، تأخير مجموعة الرسائل، فقدان مجموعة الرسائل، واي فاي، (ال تي إي)، جودة الخدمة المقدمة، وكفاءة في استخدام الطاقة.

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Dedication

To my beloved husband and family

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List of Abbreviations

ACK	Acknowledgement
AP	Access point
CCTV	Closed circuit television
CDMA	Code division multiple access
CFP	Contention free period
CSMA	Carrier sensing multiple access
CTS	Clear to send
DCF	Distributed coordinated function
EPS	Evolved packet system
FDMA	Frequency division multiple access
FTP	File transfer protocol
GMLC	Gateway mobile location centre
GPRS	General packet radio service
GSM	Global system for mobile communications
HARQ	Hybrid automatic repeat request
HSS	Home subscriber server
ICT	Information and communication technology
IFQ	Interface queue
IFS	Inter frame space
IMS	Internet protocol multimedia subsystem
IPv4	Internet protocol version 4
IPv6	Internet protocol version 6
LOS	Line of sight

MIMO	Multiple input multiple outputs
MME	Mobile management identity
NAV	Network allocation vector
NOAH	No ADHOC routing agent
OFDMA	Orthogonal frequency division multiple access
P-GW	Packet data network gateway
PAPR	Peak to peak average power ratio
PC	Point coordinator
PCF	Point coordinated function
PDN	Packet data network
QoS	Quality of service
RF	Radio frequency
RFID	Radio frequency identity
RTS	Request to send
S-GW	Serving gateway
SAE	System architecture evolution
SC-FDMA	Single carrier frequency division multiple access
SETH	Smart environmental hierarchy model architecture
TCP/IP	Transmission control protocol/internet protocol
TDMA	Time division multiple access
UDP	User datagram protocol
UE	User equipment
UMTS	Universal mobile telecommunication system
VOIP	Voice over internet protocol

WiFi	Wireless fidelity
WIMAX	Worldwide interoperability for microwave access
WLAN	Wireless local area network
WT	Wireless terminals

Chapter 1: Introduction

1.1 Overview

We live in a changing digital world. Technology has progressed remarkably, and new aspects are being developed daily. With the introduction of the Internet, followed by mobile phones, information is accessible to people in an easy and comfortable way. The term ‘smart city’ does not have a universally accepted definition. It means different things to different countries and people. In recent years, the concept of the smart city has been widely accepted because of the desire for reforming into a certain standard of living.

The objective of a smart city is to provide an adequate infrastructure and services to the citizens with the help of technology. The focus of the smart city is to provide a sustainable environment and applications of smart solutions. The smart city improves the quality of life of citizens by converting existing solutions into smart solutions. In a smart city, every citizen is connected. With advances in technology, objects are also connected, e.g., a phone and a school bus for children [1].

The urgency of smart city emerges from the fact that half of the population of the world lives in cities. It is highly important for the resource limited cities to have innovative technologies and services to improve the sustainability, competitiveness, and quality of life. The main idea is to employ information and communication technology (ICT) in urban development for creating a responsive city that satisfies the demands of knowledge-based citizens. This includes smarter city delivery networks, upgraded water delivery and waste-disposal centres, and extra eco-friendly approaches for lighting and heating homes. It also encompasses interactive and responsive town management, safer public areas, and satisfying the desires of the increasing elderly population [2] [3].

1.2 Smart City Challenges

Smart-metropolis challenges involve vital advancements in digital infrastructure, sensing, and communications. The distribution networks (such as water, electricity, and gas), transportation system, and road infrastructure in the city can be integrated with information and communications technology with improved efficiency and reliability [4].

Smart spacing is another challenge in digital infrastructure. The idea is to automatically modify the public and private spaces by adapting the requirements of the citizen. Urban sensing is an important factor in smart cities, such as the deployment of sensors and actuators for the real-time sensing of pollution levels, temperature, and traffic congestion on roads. Reforming the aforementioned challenges requires efficient data communication [5].

There is a need for integrating all accessible networks for offering adequate capacity and quality of service (QoS). The solution is aggregating wireless-sensor networks to measure physical parameters, cellular networks (including 3G/4G) to manage mobility, and mesh networks to aid recent applications and functions. The primary objective is to maintain the QoS with regard to the capacity, packet delay, and packet loss.

1.3 Technological Challenges

The challenges in technology can be divided into device communications, security, how to utilize the spectrum and backhauling.

1.3.1 Communication between Two Devices

Currently the communication is between the users so that all architectures are supporting high data rates. Now when it comes to device communication it has higher delay and lower data rate. So in order to support device communications it is peremptory that some changes have to be implemented in the communication network. These device-to-device communications increase the utilization of networks and reduce the energy wastage. However in a smart city the device management should be able to differentiate all types of devices and data access while maintaining user privacy [6] [7].

1.3.2 Security

Security is one of the primary concerns in smart cities. The privacy of users must be considered; the loss of privacy may cause the user to refrain from the world of the smart city. The smart system should be able to ensure citizen safety and respond quickly to emergencies. Intelligent applications should be able to detect fraudulent devices.

1.3.3 Spectrum Utilization

Efficient utilization of spectrum is highly important so that unused resources can be reinforced effectively. Communication and networking can be done using energy-efficient devices and communication protocols. Additionally, renewable sources can be used as power sources.

1.3.4 Backhauling

When there is large number of small cells, it is not easy to connect each of them to the main network directly; the relaying of the networks can solve this. A larger number of cells leads to more frequent handovers [8].

1.4 Smart-City Services

It is expected that a wide range of services will be available to residential users (e.g., smart management of the energy demand, intelligent transportation systems, smart spacing, urban sensing, etc.) with improved quality, reduced costs, and low environmental impact compared to the existing services. The challenges in the smart management of distribution networks are the deployment of an automatic mechanism and the handling of machine-to-machine and sensor-to-actuator communication. However, the smart transport system has challenges as the reliability and improved safety depend on people. Current smart-city services include smart infrastructure, such as wireless sensors smart transportation, the integration of ICT in a distribution network, and user-centric services improving the mobility of citizens. For example, drivers are altered of the arrival of emergency vehicles in order to clear lanes, and urban sensing is employed instead of more mobile terminals [9] [10] [11] [12].

1.5 Network Services

Because 3G or cellular network services are insufficient, for satisfying the needs of smart city services wireless-sensor networks should be part of the system. Current wireless-network architecture involves Internet Protocol (IP)-based connectivity models that are used together with Internet and smart-object networks based on a Transmission Control Protocol (TCP)/IP architecture. These protocols can be used across the devices and communication technologies. They are stable, scalable, and manageable and resolve the challenges concerning wireless-sensor networks, such as a low operational power and large scale of networks [4] [13].

1.6 Urban Population Trends and Smart Cities

The necessity for smart cities is indicated by the current trends in the urban population. Urban areas consume half of the total population worldwide, and the population is increasing at a rate of two people per second. Around three fourths of the generated electricity is consumed in cities, and 80% of carbon dioxide emissions occur in townships and urban areas. The United Nations (UN) predicts that the number of people residing in cities will increase by almost 70% by 2050. The major growth will occur in developing countries rather than developed countries [14].

Additionally, according to the UN population fund, there will be 27 major cities with millions of people by 2030. Many of these cities will be in Asia. In the past years, there has been rapid urbanization in China. As prognosticated by the City Blue Book, the urbanization in China will exceed 60% by 2030, with over a million people residing in more than 70 cities. The increase of urbanization is indicated by traffic jams, extreme pollution, and inadequate power. For example, 61% of cities in

China have water scarcity and traffic congestions at busy hours.

As resources are distorted in cities, a large amount is staked in the urban framework. Thus, a possibility exists to enhance the experience and competitiveness of the urban lifestyle in accordance with the smart city formation, technologies, and functions. The concept of smart cities is to engage ICT deeply in all factors of urban improvement to create a city according to the concerns of knowledge-based citizens [15].

1.7 Important Considerations for Smart Cities

1.7.1 Scalability

For connecting different kind of devices across the sensor networks, high network scalability is required for a good smart-city experience. For this small cell, base stations play a vital role in providing a high capacity and enough coverage for future traffic.

1.7.2 Compatibility

The devices should be compatible and can be easily upgraded to update software without disturbing the user.

1.7.3 Programmability and Automation

The software technology can improve the network capability, and a software defined network can expedite planning and management [16].

1.8 The Proposed Network Structure

In the literature, smart-city applications have employed different networks, but one at a time. In this research, we propose a new network structure for smart cities that can support a wide variety of smart city services with any required level of QoS. In the proposed structure, smart city sensors are connected wirelessly using two network interfaces. One is connected to a public WiFi network, whereas the other is connected to a 4G (LTE) mobile network. Using extensive computer simulation, we study the performance of the proposed network structure compared with single interface wireless sensors (connected to either WiFi or LTE). We show that the proposed structure outperforms single-interface networks in all aspects including the overall energy consumption. We also present a study of the impact of changing a wide set of network parameters on the performance of proposed structure.

1.9 Thesis Organization

Chapter 2 provides a background and discusses work related to the thesis, including the performance of smart-city applications in different wireless-networking environments. Chapter 3 describes the system model in detail. Chapter 4 explains the performance study, which involves various experiments. Chapter 5 provides a summary and discusses directions for future work.

Chapter 2: Background and Related Works

2.1 Smart-City Structure

In this chapter, topics related to the thesis objectives are discussed with the help of figures and tables. The topics are divided into the smart-city structure; smart-city architecture and various technologies used thus far, and related works. Regarding the smart-city structure, various layers of the structure are discussed. Regarding the architecture, different types of topologies and implementations of the architecture are considered. Smart cities can be implemented by using different kinds of technologies, all or some of which may work together.

In general, the building blocks of the smart-city architecture are as follows:

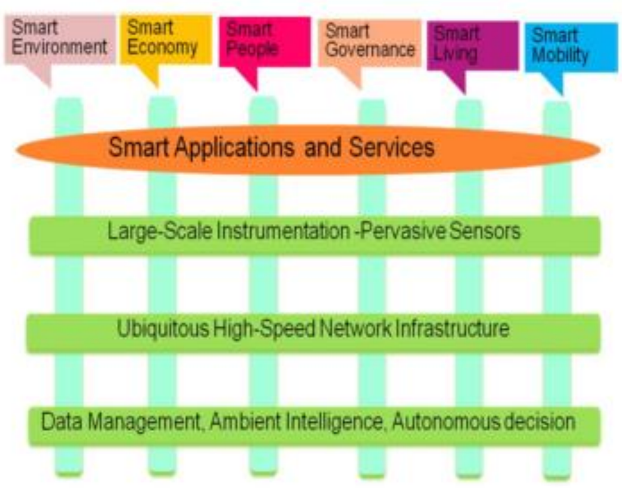

Figure 2.1: Building blocks of smart city architecture [17]

The smart environment represents the efforts directed towards a safe and welcoming environment, including controlling the pollution and efficient resource management. The smart economy is concerned with the attractiveness and competitiveness of the region with regard to factors such as the stimulation of innovation, entrepreneurship, productivity, and international appeal. The word "smart people" does not refer to education or intelligence but indicates how adequately and openly the citizens communicate within and outside the city [7].

The term 'SMART Governance' represents the future of the public services. It involves being highly capable, with improvement through transformation. SMART Governance involves the use of technology to expedite and improve disposition and ruling. Smart living consists of the concerns expected to affect the characteristics of life within the region, such as the culture, health, security, and traveller attraction. Smart mobility guarantees fuelling the technologies of the future. The power consumed by an electric train is far lower than that consumed by the normal combustion engine train. We can also improve the stability of smart vehicles by integrating the battery with the power grid [17].

In general, a cloud-based architecture has three layers. The first layer is the sensing layer and consists of numerous sensors used for different applications. This layer is used for collecting information from the sensors. In this layer, there are wireless-sensor nodes, radiofrequency (RF) devices, and mobile phones for human participation. These can all communicate with each other using various technologies, such as Bluetooth, Zig Bee, and WiFi. They exchange information with the network layer through various gateways, where the data processing occurs [18].

Different gateways are used for RF identification, wireless sensors, and mobile phones. In control centres, a web interface is used to communicate between different databases community and services. There are two types of control centres: individual and community control centres. There are service providers in both the control centres, and the community centre provides services to the community, rather than to individuals [19].

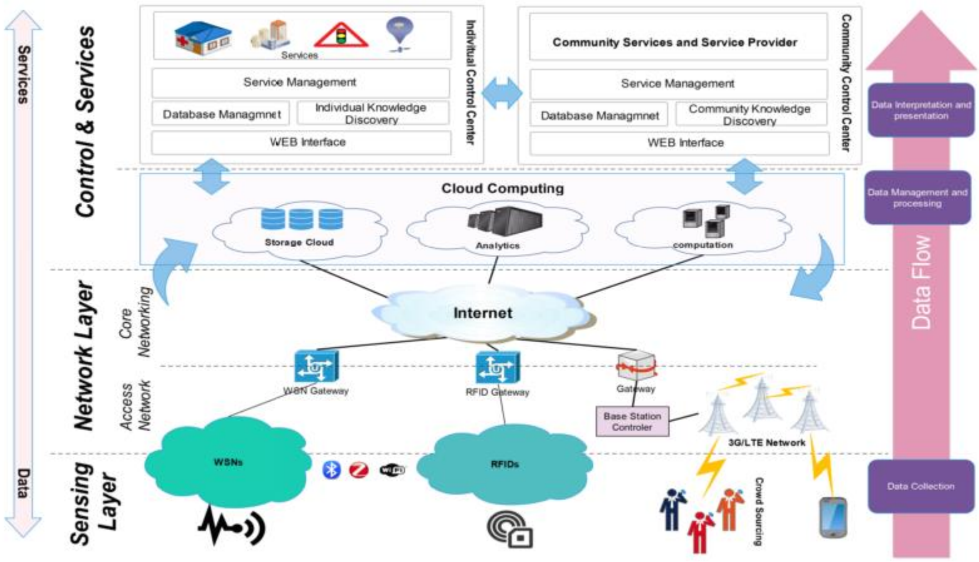

Figure 2.2: Different layers in smart city architecture [19]

2.1.1 Choosing Smart-City Architectures

The smart-city architecture can be selected according to the network design or the connectivity model. There is two design approaches: the evolutionary approach and the clean-state approach. In the evolutionary approach, the existing architecture is upgraded and many components are used, whereas in the clean-state approach, the existing architecture is redesigned. IP-based connectivity models are widely accepted because the network architecture is compatible with wireless-sensor networks, as well as smart-object networks.

2.2 Smart-City Architecture

2.2.1 Autonomous Network Architecture

We have chosen evolutionary-design, IP-compatible model with a network hierarchy and low QoS complexity. In this architecture, the network is not always connected to Internet but can be connected through a gateway. Most systems operate in a three-tier mode. The basic tier communicates with the sensors. The intermediate tier forwards the communication to the next level. The final tier communicates with the Internet gateway [20].

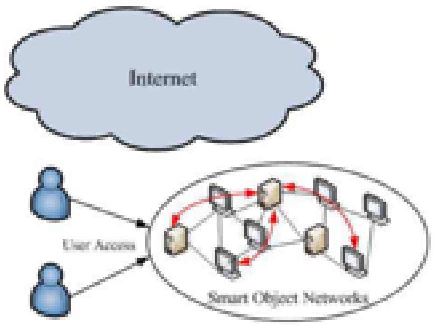

Figure 2.3: Autonomous network architecture [20]

Application: Automatic parking management

The automatic parking system gives the citizens access to vacant parking lots via their smartphones. Additionally, the city service council can administer fines for violations. The range of sensors, the sensor accuracy, and the speed of response are the important parameters in parking management [20].

2.2.2 Ubiquitous Network Architecture

The ubiquitous network architecture is an IP-based architecture. It is an evolutionary hierarchical network. The ubiquitous network architecture is multitier (consists of wireless multi-access networks and multi-hop networks) and multi radio (consists of different types of radio access technologies, such as wireless local area network (WLAN), Worldwide Interoperability for Microwave Access (WIMAX), macro cellular, and femto cellular). Smart-object networks are part of the Internet. Through the Internet gateway, authorized users can access information. When there are real-time data in the multi-access wireless networks, it is difficult to satisfy the different QoS requirements [20]

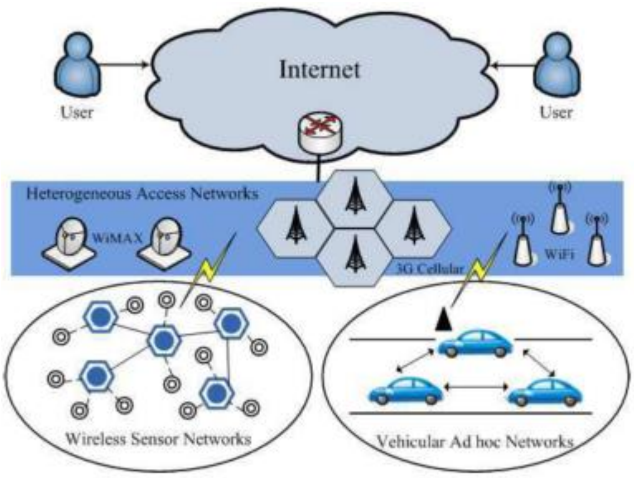

Figure 2.4: Ubiquitous network architecture [20]

Application: Traffic congestion and impact monitoring.

Various sensors can be used to measure the traffic congestion and pollution levels due to the traffic by communicating with vehicles (movable) and also from fixed locations. The pollution levels due to the traffic and the traffic congestion can be detected using different types of sensors by communicating with moving vehicles and from stationary points. Using car-to-car and car-to-machine networks, the timing for travel can be managed online, and the source and destination map can be monitored for checking the congestion, noise emissions, etc.

2.2.3 Application Layer Overlay Network Architecture

This is IP-based evolutionary-design hierarchical network architecture. Because data are collected from thousands of nodes, the QoS may decrease, and congestion occurs at the receiving point.

Application: Environmental monitoring and sensing

Urbanization and climate changes have caused environmental pollution, which must be monitored because it affects the air quality. Various parameters—such as carbon monoxide, benzene, and ammonia—can be measured, along with the temperature and humidity levels. Because the traffic is elastic in nature, the bandwidth is important where the delay can be tolerated [20].

2.2.4 Smart Environment Hierarchy (Seth) Model Architecture

As indicated by its name, the SETH architecture follows a hierarchy. The key concepts in this architecture are the hierarchical arrangement of smart spaces and the use of agents responsible for learning the interests of the user. The main challenge is the user mobility. The mobility of the user is not uniform; thus, agents are defined in the system. The stationary agents are located at a single smart space, regardless of the user movements. The nomadic agents can be placed in a smartphone, which the user can carry [21].

2.2.5 Stem Node Network Architecture (Stem-Net)

New generations of network nodes are capable of delivering intelligent services for people and municipal administration. STEM-NET is a wireless device that adjusts according to the communication requirements. Its functionality can be changed to achieve the goals of the network. Multi homing can be achieved using STEM-NET.

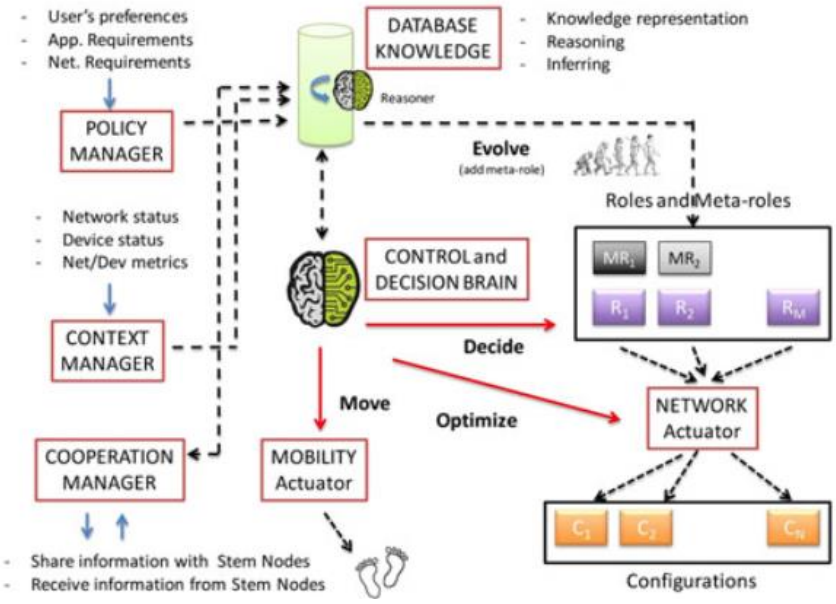

Figure 2.5: STEM-NET architecture [22]

In this architecture, each stem node is assigned a specific role. A role is an inbuilt function that the device can perform. Meta roles are defined as functions that the node can perform after collaborating with other devices. Meta roles are performed after a stage called evolution, during which the stem node plays the roles of other devices [22].

2.2.6 Evolved Packet System (EPS)

The EPS enables multiple accesses to the same user in order to perform multiple tasks simultaneously. The EPS can provide a different QoS for each task [23].

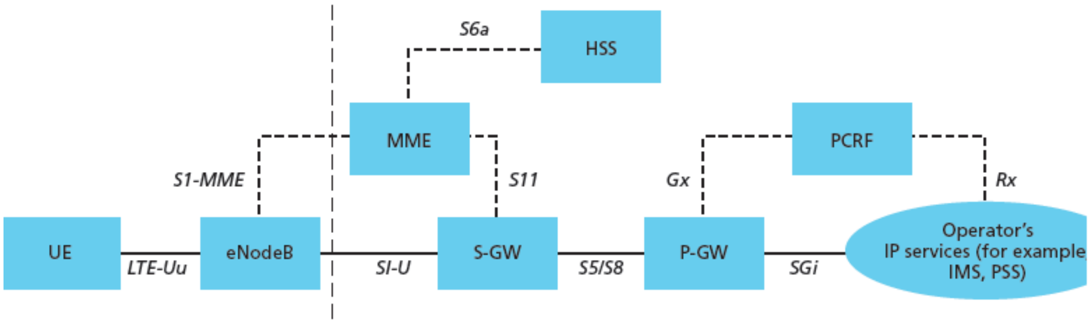

Figure 2.6: Evolved packet system architecture [23]

Evolved packet system architecture supports simultaneous voice call (VOIP) and FTP (file transfer protocol) download or web browsing. Apart from this IMS (IP multimedia subsystem), UE (user equipment) positioning and enhancement to home cells are also supported [23].

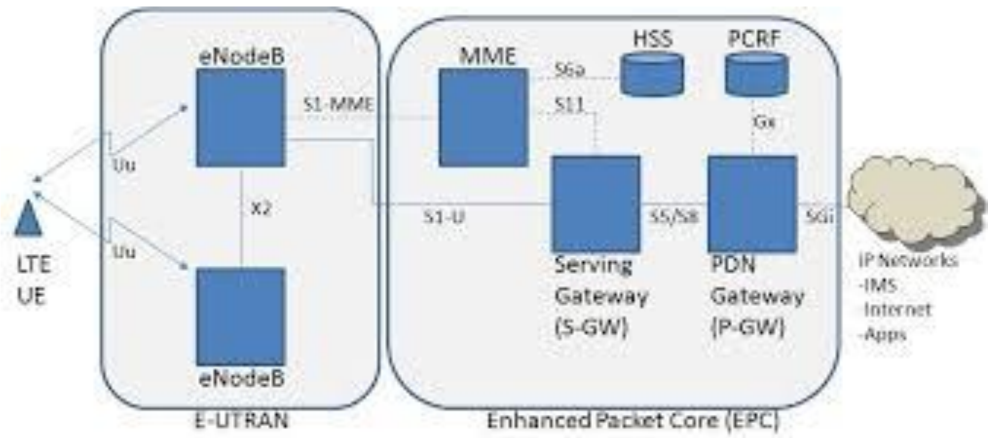

Figure 2.7 EPS network architecture [23]

Application	Capacity	Bandwidth	Delay
Email	High	Low	Low
File transfer	High	Medium	Low
Telephony	Low	Low	High
Video conference	Low	High	High

Table 2.1: The QoS requirements varies based on applications [24]

The sensor networks require a large number of nodes. The IPV6 protocol can handle 10^{38} nodes, but most of the sensor networks sleep when not in use, to save energy. Thus, it is better to implement an architecture based sensor network. The LTE and LTE Advanced (LTE-A) networks can be effective in these cases.

2.3 Related Technology

Regarding wireless networks, there are two topologies or techniques whereby the mobile terminals communicate: infrastructure-based and ad hoc-based.

In the infrastructure-based method, the mobile stations are connected to each other via an infrastructure (base stations or access points (APs)), whereas in the ad hoc approach, the mobile stations are connected to each other and no infrastructure is required for connectivity. Because we are focused on smart-city services that cover a wide area, we consider the infrastructure-based topology.

2.3.1 Cellular Topology

The main concept in cellular topology is frequency reuse. There is a large demand for capacity, and it is extremely important to efficiently use the spectrum by choosing an appropriate architecture. The basic concept in the cellular network is to divide the coverage area into numerous cells. The cells are grouped into clusters. The number of cells in the cluster is the frequency-reuse factor. The concept of cellular topology can increase the number of customers that can be supported in the available frequency spectrum. As the cellular topology is changed to reduce the coverage requirements, less power is required by the mobile terminal to communicate with the network. Increasing the number of cells can increase the network capacity and reduce the size of the mobile terminal. On the other hand, a larger number of cells results in more complexity and cost in deploying the networks, as well as more handoffs. The design of the cellular topology should balance all of the aforementioned factors.

2.3.2 Cellular Hierarchy

The hierarchical cellular infrastructure has different cell sizes. Having different cell sizes is very important because there may be many customers in one area and less in another area. Additionally, the coverage area includes we may come across wide-open places and the insides of the buildings. A single cell size cannot satisfy these different requirements. According to the hierarchy, the different cell sizes are defined.

Femto cells are smallest cells in the hierarchy. They cover only a few meters and are mainly installed by users, to extend the cellular-network coverage. Femto cells can autonomously determine their frequency and power, with partial management by the cellular-network operator. Pico cells can cover a range of a few tens of meters. They are mainly used inside buildings. They support indoor networks, such as WLAN. Micro cells can cover a range of hundreds of meters (such as streets). They are mainly used in urban areas. Macro cells can cover a very large area (several square kilo meters). Their antennas are often mounted on the rooftops of tall buildings. Mega cells can cover nationwide areas, with a range in the order of kilo meters, and are mainly used by satellites [25].

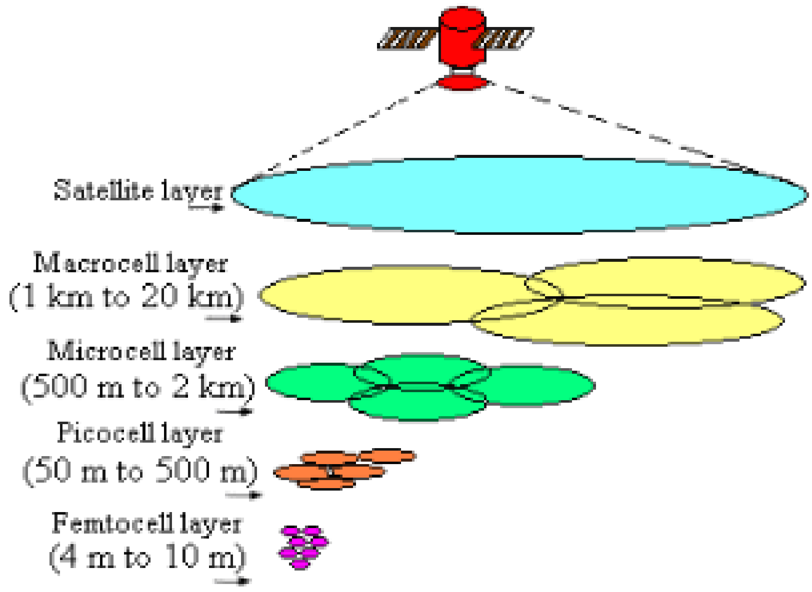

Figure 2.8: Cellular network hierarchy [25]

2.3.3 Cellular-Capacity Expansion Techniques

There are different techniques for expanding the capacity of a cellular network. The first is the introduction of an additional spectrum. This is the simplest but most expensive method. The second is to change the architecture via cell splitting, sectorization using directive antennas, and multiple reuse factors. The third is to change the uniform frequency allocation to a non-uniform distribution. Amending the access technology is the fourth method. Beginning with analog technology using frequency modulation, cellular access technology has implemented digital technology, such as time-division multiple access (TDMA), code-division multiple access (CDMA), etc. There are different methods for expanding the capacity of the cell. One method is cell splitting. When the number of subscribers in a particular area increases, the number of channels allocated to the cells may be insufficient to meet the demand. Thus, additional channels must be allocated. This can be achieved by splitting cells. The problem with this technique is that it reduces the capacity of larger cells and yields a chain of splitting cells that may never end. Another method is cell sectorization. The simplest way is using bidirectional antennas for sectorization. This increases the capacity by reducing the signal-to-interference ratio and cluster size. The bidirectional antennas reduce co-channel interference by directing the propagation.

2.3.4 LTE

LTE is an efficient technology for mobile phones and data terminals used in high-speed wireless communication. LTE is the fourth-generation mobile network and is expected to provide a data rate of 300 Mb/s. LTE networks evolved from the following three technologies: multicarrier technology, multiple-antenna technology, and the packet-switched radio interface. The uplink transmission in LTE employs single-carrier frequency-division multiple access (SC-FDMA), and for the downlink transmission, orthogonal frequency-division multiple access (OFDMA) is used. OFDMA provides a very flexible multiple-access scheme. The advantages of OFDMA include robustness for radio channels and low-complexity receivers. In the uplink transmission, the peak-to-average power ratio (PAPR) is high, whereas the PAPR for SC-FDMA is relatively low. With multiple antennas, we can have a higher spectral efficiency with less transmitter and receiver antennas. There are three basic principles for multiple antennas. Improved transmission can be achieved due to multiple antennas with less multipath fading. With multiple antennas, through beam forming, multiple users can be served simultaneously. Multiple antennas are used to send independent and separately encoded data called streams. In LTE, the packet duration is 1ms, to ensure low system latency. The main features of LTE are as follows. The rate of 376.88 Mb/s can be increased to 500 Mb/s. In a downlink spectrum of 20 MHz, 100 Mb/s is the peak instantaneous downlink rate. Similarly, in an uplink spectrum of 20 MHz, 50 Mb/s is the peak instantaneous uplink rate. The most favourable cell size is 5 km. A rational performance is obtained with a cell size of 30 km. With a cell size of 100 km, an adequate performance is expected. In a 5-MHz cell, there can be a maximum of 200 users active in the cell. Although LTE supports a high speed, the mobility is in the range of 0–15 km/h [23].

LTE technology accords with the other lineage standards, such that the existing call or data transfer using the LTE standard can be continued when it goes out of the coverage of LTE using the Global System for Mobile Communications (GSM)/General Packet Radio Service (GPRS).

2.3.5 LTE-A

The downlink peak rate of 150.752 Mb/s can be increased to 1.5 Gb/s via carrier aggregation. The uplink peak rate of 376.88 Mb/s can be increased to 500 Mb/s via carrier aggregation. Carrier aggregation allows the extension of the bandwidth over multiple carriers by using resources. The spectrum of LTE-A is three times more efficient than that of LTE. The peak efficiency of the spectrum for downlink and uplink transmission is 30 and 15 bps/Hz, respectively. Because LTE-A is capable of using a scalable bandwidth and spectrum aggregation, a lower limit of 40 MHz and an upper limit of 100 MHz can be achieved for the bandwidth. The delay is less than 5ms in packet transmissions, whereas it is less than 50ms in the connected state and less than 100ms in the idle state. The throughput is higher than that for LTE. LTE-A is adaptable with LTE and 3GPP systems [23].

2.3.5.1 Advantages of LTE-A Over LTE

To extend the bandwidth, multiple carriers are used, along with multiple input, multiple output (MIMO) techniques. According to International Mobile Telecommunications, it is feasible to utilise LTE terminals for LTE-A [26][27].

The range and network of the cell can be increased in LTE-A, by deploying the relay nodes near the cell edges. The better option is to decode and forward relays; otherwise, the interference is amplified along with the signal.

The capacity can be maximised by applying the iterative water-filling algorithm to wireless terminals (WT) that function as relays. However, for fairness between the WTs, scheduling and routing algorithms must be employed. There is global fairness and local fairness. Local fairness can be achieved by maximizing the harmonic mean rate. However, global fairness is difficult to achieve, as WTs communicate only with their immediate neighbours.

The cell coverage can be increased via the beam forming technique, which allows the use of antenna arrays for increasing the cell edge coverage by using relays, heterogeneous networks, and MIMO technology [28].

2.3.6 WiFi

The standard Institute of Electrical and Electronics Engineers (IEEE) 802.11 was implemented in the year 1997. This standard focuses on local area networking with wireless connectivity. IEEE 802.11 defines the physical layer as well as the medium access control (MAC) layer of LANs.

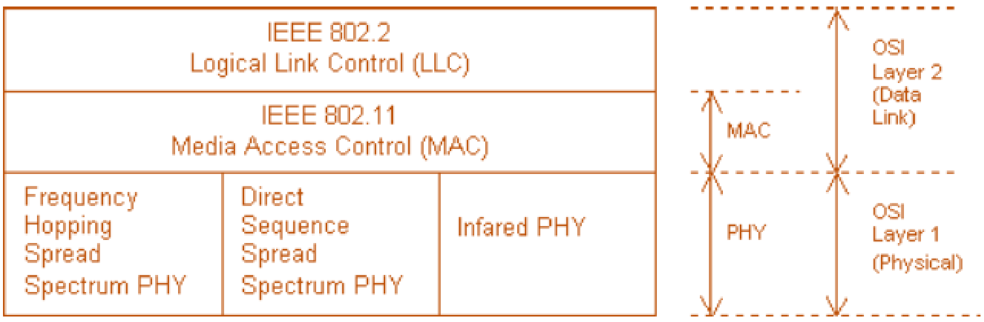

Figure 2.9: IEEE standards with the Open Systems Interconnections (OSI) model layers

WiFi is a networking protocol that allows devices to communicate wirelessly. WiFi follows the network standard of IEEE 802.11. It is the most widely accepted wireless communication and is preferably operated using a static source node. WiFi and the IEEE 802.11 standard are always interesting for engineers, and studies to find better solutions are underway. WiFi networks provide a better broadband experience than heterogeneous networks. They also help the cellular network to offload some data traffic. Many studies have concluded that in densely populated areas, more than 65% of the traffic can be offloaded. IEEE 802.11 is a family of random-access protocols with similar medium access mechanisms (but different physical layer implementations). IEEE 802.11 was adopted in 1997 and is used in all WiFi networks. It describes the physical layer, the MAC sub layer, and the MAC services and management protocols [29].

2.3.6.1 IEEE 802.11 Architecture

The two important components in the IEEE 802.11 standard are the station and the AP. Any source with a wireless network interface card can be considered as a station. Any transit point between the fixed and wireless networks can be treated as an AP. The AP can be designated as the base station, by incorporating the wireless stations into the fixed network. The AP should have a network card, a transmitter, and a receiver, as well as software compatible with IEEE 802.11. There are two modes of operation in IEEE 802.11: infrastructure and ad hoc [30].

The infrastructure mode employs a connection-oriented network that means a fixed network through the AP. As previously mentioned, the system is divided into cells. Cells that share the same MAC protocol and bandwidth are grouped together (clusters) as shown in figure 2.10 (a). In the ad hoc mode, there is no coordinator; the wireless stations are all distributed as shown in figure 2.10(b).

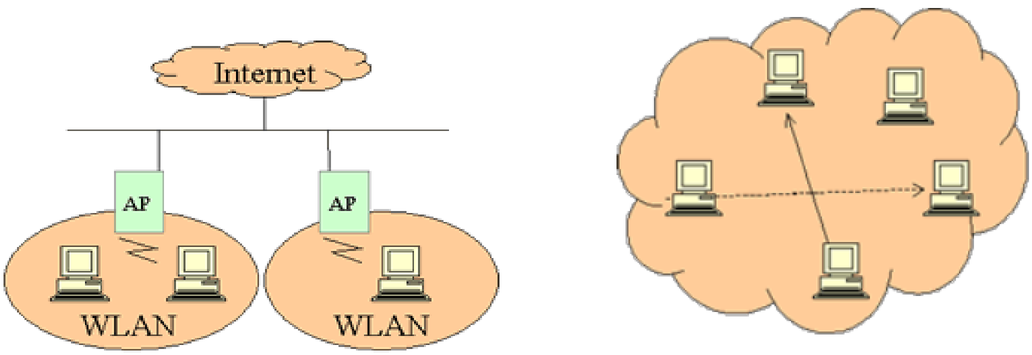

Figure 2.10: (a) Infrastructure mode (b) Ad hoc mode

2.3.6.2 Channel-Accessing Mechanisms In IEEE 802.11

The distributed coordinated function (DCF) and point coordination function (PCF) are the two channel-accessing mechanisms in IEEE 802.11.

2.3.6.2.1 Distributed Coordination Function

The DCF is based on the carrier sense multiple access (CSMA) mechanism. It employs asynchronous best-effort data transfer for delivering the basic access service. All stations can access the medium. The stations prepare to access the medium. The stations that are ready wait for any existing transmission to be completed. All the stations must also wait for a particular amount of time called the inter-frame space (IFS). If a station needs to transmit information, the first step is to sense the channel. After waiting for the IFS duration, the station can begin the transmission. If the channel is engaged, after waiting for the IFS duration, the station must wait for a back-off timer, which is generated in randomly. In each time slot of the timer, the station can sense the channel. The back-off timer stops when any other station engages the channel; the timer stops and restart only when the channel becomes idle.

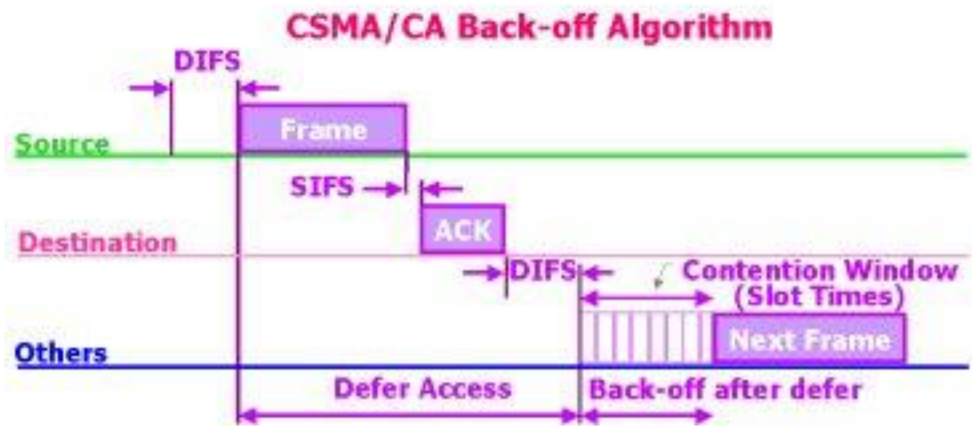

Figure 2.11: Medium access in DCF using two-way handshake

DIFS: DCF IFS

PIFS: PCF IFS

SIFS: Short IFS (Acknowledgement (ACK/request-to-send (RTS)/clear to send (CTS))

There are two techniques for packet transmission in the DCF: two-way handshaking and four-way handshaking. In two-way handshaking, a transmission is considered successful when an acknowledgement from the destination station is transmitted to the sender station. Four-way handshaking employs an RTS/CTS mechanism [29]. Consider the following example.

There are three stations in the network: A, B, and C. C cannot sense the transmission from A. If A has a frame to send to B, it sends an RTS frame. In the RTS frame, A includes the duration of transmission for the data frame. When B receives the RTS, it broadcasts a CTS frame. Both A and C receive the CTS frame. When C receives the CTS frame, it knows the duration that the data frame of A will take. C waits until A finishes its transmission before it sends any RTS frames to B.

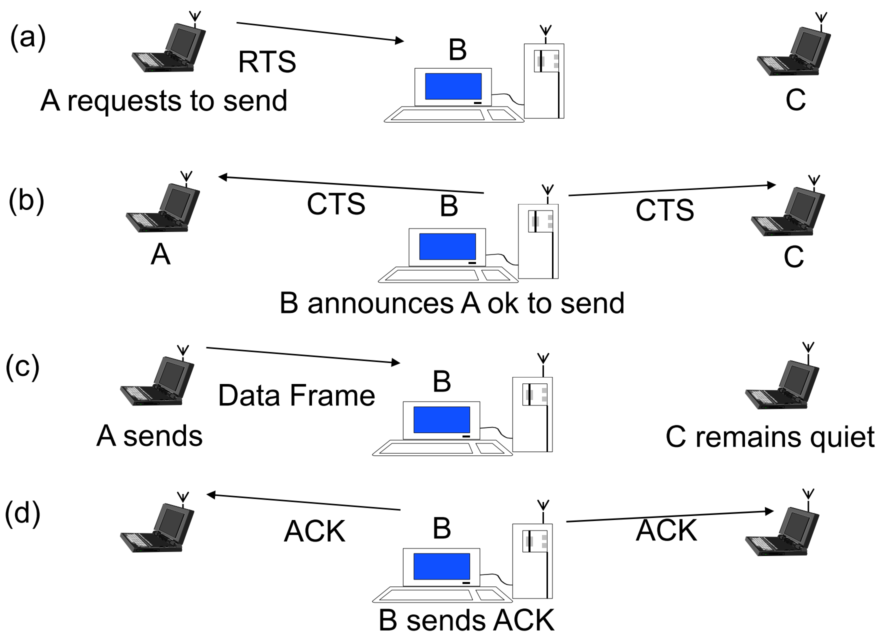

Figure 2.12: Medium access in DCF using four-way handshake

2.3.6.2.2 Point Coordination Function

The PCF uses polling to avoid contention and ensure connection-oriented functionality. The AP in the point coordinator (PC) implements the PCF. The AP determines the polling table. The collision-free period (CFP) repetition interval decides the prevalence rate of CFP occurrence. The AP sends a beacon frame that triggers the point coordination. During the CFP, the stations can only reply to a poll or transmit acknowledgement.

The process for the PCF is as follows. The channel is sensed as idle for a PCF IFS period. A beacon frame transmitted by the PC initiates the CFP. The beacon frame contains the CFP repetition interval (CFP rate), which determines the frequency of CFP occurrence. Part of the CFP repetition interval is dedicated to contention-free traffic, and the rest is for contention-based traffic. The beacon frame also contains the maximum duration of the contention-free period: CFP_max_duration. All the stations should adjust their NAV to the CFP_max_duration once they hear the beacon frame. During the CFP, the stations can only transmit in response to a PC poll or an ACK frame [29].

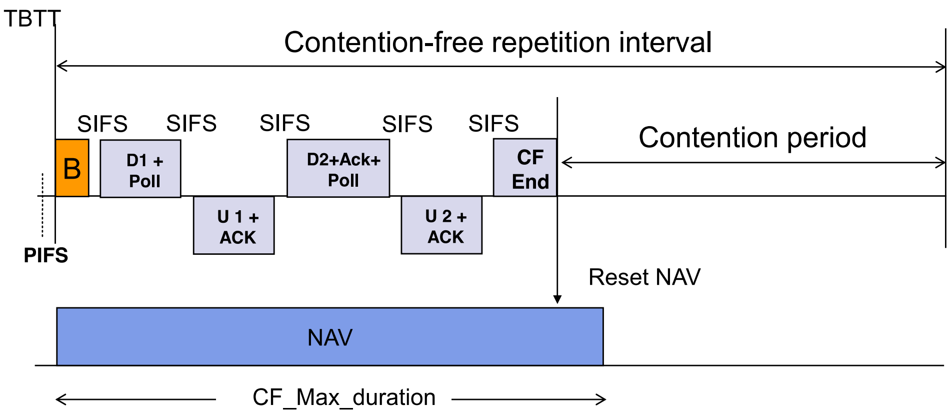

Figure 2.13: Medium access in PCF

In accordance with the IEEE 802.16 standard, WIMAX can access the wireless broadband, which can replace the digital subscriber line and cable. The principles of a WIMAX network are as follows. There are unlicensed and licensed spectra. Different kinds of radio access network (RAN) topologies employ WIMAX.

The unbiased RAN structure implements consistent connectivity and collaboration with the 3GPP, 3GPP2, and WiFi networks. The IP integration reinforces the collaboration of IPv4 and IPv6 in connecting the clients and servers. The fixed access is broadened to mobile devices with the broadband multimedia functions, which are supported by mobility management.

	WiFi	**WIMAX**
IEEE standard	IEEE 802.11	IEEE 802.16
Data services	Local area networks	Broadband wireless access in Metropolitan area networks
Frequency band	2.4 GHz	2 G -11 G Hz
Channel bandwidth	25 MHz	1.25 -20MHz
Radio technology	DSSS	OFDM
Duplex (Half/Full)	Half	Full

Table 2.2: Comparisons between WiFi and WIMAX

2.3.7 ZigBee

ZigBee is an architecture developed in accordance with IEEE 802.15.4. It is considered to have a low data rate but can be focused on the needs of applications and customers. The major applications of ZigBee are security systems, patient monitoring, consumer electronics, and environmental energy management. As shown in Figure 2.15, different topologies can be considered for a mesh network. The mesh network improves the reliability and increases the range. The data rate ranges from 20–250 Kbps, and the data transfer can be acknowledged [31].

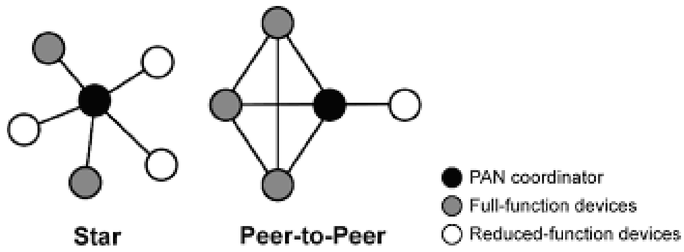

Figure 2.14: Different topologies in ZigBee

2.3.8 Bluetooth

Bluetooth technology allows communication between devices in a short range. Bluetooth is standardised under IEEE 802.15.1. There are two requirements for Bluetooth communication: the devices should be discoverable, and there must be a circuit established already. Bluetooth communication follows a master–slave principle.

2.4 Related Work

2.4.1 Public Traffic Lighting in the City of Padova, Italy

For the public traffic lighting system in the city of Padova, a smart application is developed. Wireless nodes and various sensors are positioned on light poles and connected to the Internet for monitoring the public street lighting. The measured light intensity is used to monitor the air pollution, degree of hotness, sound pollution, etc. The light level is measured by photometer sensor attached to the nodes. These sensors can indicate the light intensity in a fixed interval of time or when needed. They can also measure the degree of hotness and the moisture level in the atmosphere, providing information related to the climate. The air quality is observed using a benzene (C_6H_6) sensor. Internet of Things (IoT) nodes are low-power devices that can be installed anywhere. The total area of Padova city is 92.85 km^2. Considering a highway 100 km long, for maintaining a distance of 50 m between sensors, we need approximately 2,000 sensors [32].

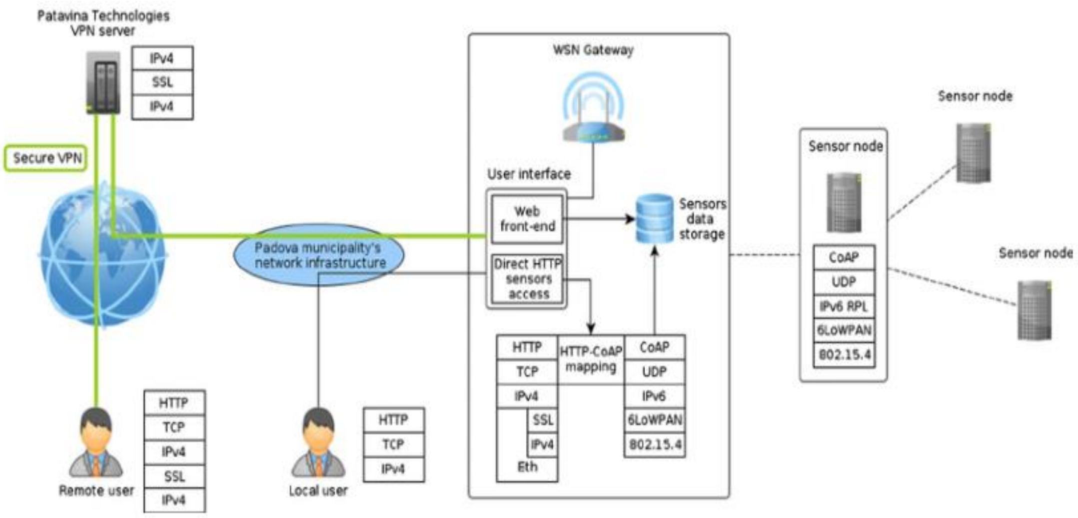

Figure 2.15: Padova smart city architecture [32]

2.4.2 Smart community healthcare

In this architecture, various sensors are used to detect the heart rate, blood pressure, and patient position. The information collected from the sensors is transmitted via Bluetooth technology. It is also transmitted to control centres through 3G or LTE technology. The health community tracker for data analysis can use the database in the control centre [19].

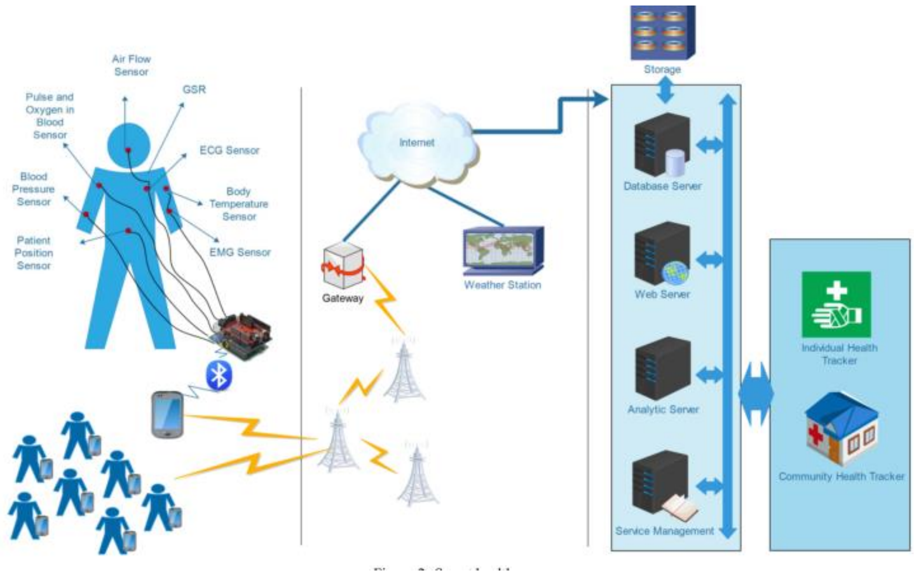

Figure 2.16: Smart healthcare architecture [19]

2.4.3 Barcelona WiFi

Barcelona WiFi is a Barcelona City Council service that allows users to perform simple Internet browsing through WiFi APs, i.e., hotspots, located in various municipal amenities. The connection has a speed limit of 256 Kbps. To maintain the availability of Internet resources for users, the system disconnects after 30 min of inactivity.

WiFi APs theoretically have a radius of 20–50 m in closed spaces and 100–150 m in open air. These figures may vary considerably depending on the surrounding conditions (barriers, interference, etc.) [33].

2.4.4 Smart Lighting Applications

The wireless-sensor networks are used to implement a smart-lighting system. The main concept is rational and efficient energy usage. This helps to reduce the cost of public lighting via the automatic detection of failures, remote control, and reducing the energy consumption. The architecture of the system is shown below

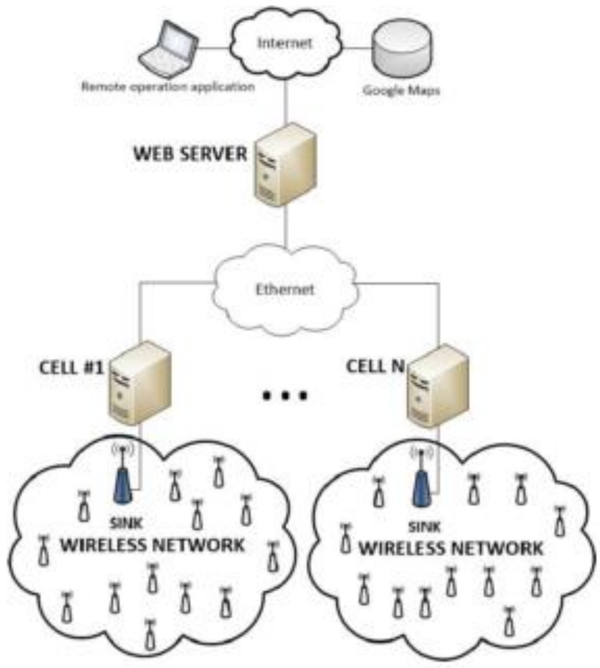

Figure 2.17: Urban lighting architecture

The cells communicate with the controller of the system, whereas the sinks communicate with the nodes through the wireless network. Any number of cells can be created to cover an entire urban area [34].

Chapter 3: System Model

3.1 Introduction

This chapter explains the proposed system model in detail. The objective is to clarify the network configuration for the simulations and results presented in the following chapters.

3.2 Problem Statement

The objective of the thesis is to find a smart network solution for smart-city services. Updating or improving the existing solutions to smart solutions or by developing innovative smart solutions can do this. In a smart city, there are real-time and non-real time applications. Consider a smart city area of 100 m^2. As shown in the figure 3.1, there are sensors and devices that can send real-time transmission as well as non-real-time transmission. They collect the data and send it over a period of time. These operations can be performed periodically or on demand. Examples of real-time transmission are surveillance cameras for monitoring traffic or maintaining building security. Cameras are also used in traffic intersections to capture images for traffic offenses, such as crossing a red signal. Servers can handle 84 closed-circuit television (CCTV) or even more, whereas devices can support a maximum of 16 channels. Applications can be accessed by the type of user and is independent of the user location. The system can be synchronised with short message service, email, etc. The CCTV recordings must be sent across the network in real time. Increasing the number of CCTV cameras adds more real-time transmission, which is a challenging task.

An application such as a heating, ventilation, and air conditioning system connected to a bus station can automatically detect the people and use weather information from the Internet to heat or cool the bus station. For vehicles entering a parking lot of a shopping mall, a display on the dashboard can show a convenient and nearby parking spot. Different sensors and devices can be connected to the WiFi and LTE networks simultaneously. For example, wearable devices allow people in a smart city to be alerted of variations in their pulse rate and blood pressure and guide them to nearby hospitals through their smartphones. They may also send messages to the emergency department. For this, the wearable devices and phones should be connected to the network at all times. The water and electricity consumptions are monitored using smart meters and sent using the LTE network to the utility department fortnightly.

Wireless-sensor networks can be used to check the number of people in a particular place, such as a public park or a shopping mall. Temperature sensors and humidity sensors can be used to monitor the whole area. Motion detectors on roads can ensure that there are no traffic blocks. If there is an unusual piling up of vehicles, this can be reported to a traffic-control unit, and a display placed on a road behind the road with traffic can alert drivers to take an alternate route.

3.3 Challenges and Proposed Study

Some sensors and devices use low data rates. However, with a large number of low-data rate sensors and devices, satisfying certain QoS level becomes a challenging task. We use the existing WiFi and LTE networks to overcome this challenge. We propose a network structure where smart city sensors are connected to both WiFi and cellular network (LTE network). Indeed, the WiFi and the LTE networks in an urban city have background traffic, such as voice calls and data transfer. With a large number of sensors and devices, there can be large accumulated demands for bandwidth. This may lead to decreasing the transmission rate and possibly increasing the number of retransmissions, which eventually lead to large power consumption. Our proposed network structure aims at reducing the power consumption of smart city sensors while satisfying the QoS level required by different smart city applications with a minimal impact on the original background traffic (of WiFi and LTE networks).

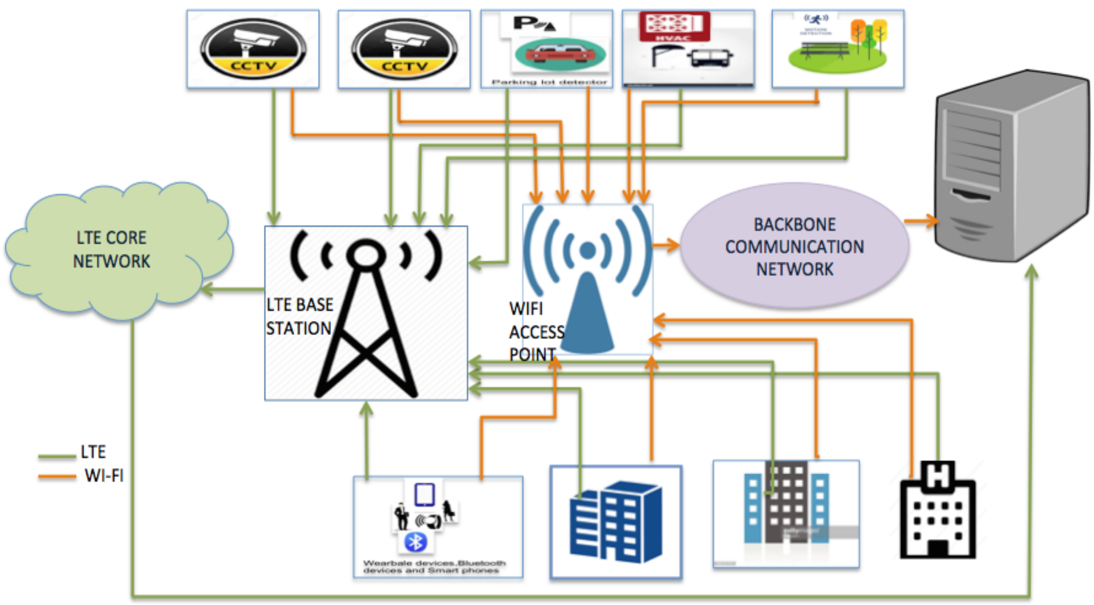

Figure 3.1: Proposed system model

Consequently, the proposed network configuration aids the deployment of smart-city devices and sensors by assuring the connectivity performance using the existing networks. Additionally, the impact of the energy consumption due to the added traffic in the existing networks is considered. As shown in Figure 3.1, all the devices are connected to the WiFi and LTE networks simultaneously to ensure smooth data transmission.

The QoS can be improved by forwarding information through relevant integrated structures that conserve the consumer fulfilment, as well as the network resources.

Thus, we can ensure a high data rate for transmitting information. Some devices with high data rates are connected to both the WiFi and LTE networks to ensure the required bandwidth. For instance, surveillance cameras that operate in real time must send data at a high data rate. Some other devices may need to send data in real time, e.g., wearable health devices. These devices may operate through smartphones, and we must ensure that the smartphones are connected to the WiFi and LTE networks. Bandwidth-hungry devices should function effectively in our proposed architecture. We assume that the wired connection between the AP and the server, as well as that between the base station and the server, has a high data rate with almost no congestion and has sufficient capacity compared to the existing network. When we come across a delay in the wireless part of the network, we still consider the overall delay to be only slightly larger than that obtained from the wireless part.

3.4 Communication Layers

3.4.1 Physical Layer

During communication between the sensor nodes and the server, the bits are transmitted in the physical layer. The attenuation of the signal in the physical layer depends on many factors, such as the distance between the transmitter and receiver and the height and location of the antennas. In signal propagation, there can be path loss, shadowing, and multipath fading. Figure 3.2 describes the relationship between the ratio of the received power to the transmitted power and the distance [30].

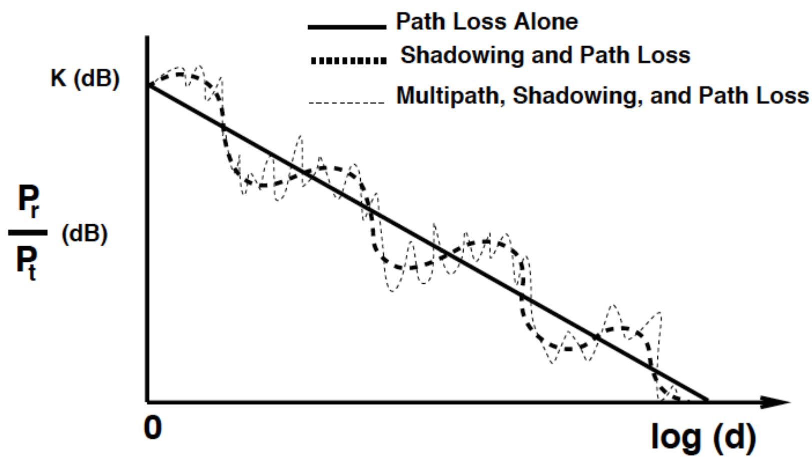

Figure 3.2: Path loss, shadowing and multi path fading versus distance [30]

3.4.1.1 Path Loss

In general, when an electromagnetic wave traverses space, there is a decrement in the power level, which can be called path loss or path attenuation.

In defining a system model, a path-loss model is necessary for analysing account the link budget. Regarding the path loss, different research models can be used, depending on the area selected. We can use a model suitable for urban areas [35].

3.4.1.1.1 Path-Loss Models

There are empirical, semi-empirical, and deterministic models.

Empirical models are generally not very accurate, depending on the statistical properties. Semi-empirical models consider the statistical properties, as well as some deterministic aspects. The deterministic model requires geometric information, is computationally complex and is accurate [30].

3.4.1.1.2 Free-Space Path-Loss Model

Assuming that there are no obstructions between the transmitter and the receiver, the signal propagates in a straight line. Thus, the received power increases as the carrier frequency decreases.

The free-space path gain is $P_G = -P_L = 10\log_{10}\frac{G_l}{(4\pi d)^2}\lambda^2$ [30]

P_G is the path gain.

P_L is the path loss.

G_l is the product of the field radiation patterns of the transmitting and receiving antennas in the line of sight (LOS) direction.

d is the distance between the transmitter and the receiver.

λ is the signal wavelength.

3.4.1.1.3 Ray-Tracing Model

The ray-tracing model can be used for urban or indoor areas where the transmitted signal can undergo reflection and scattering, resulting in different versions of the transmitted signal at the receiver end. These signal components may create distortion at the receiver end. We can apply ray tracing by assuming a finite number of reflectors. However, this model is computationally complex.

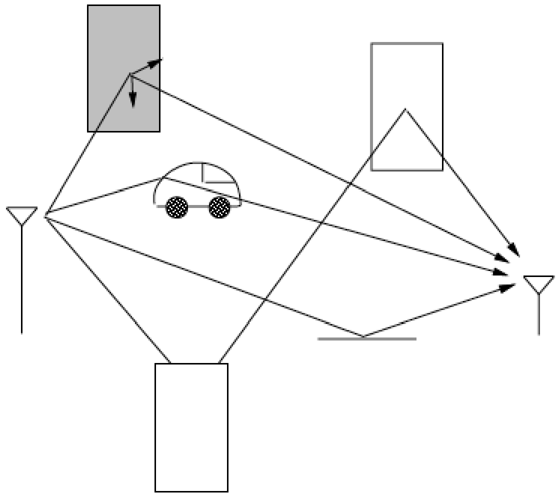

Figure 3.3: Ray tracing model [30]

3.4.1.1.4 Two-Ray Model

The two-ray model is considered when we have a dominant single ground reflection than the multipath effect. This model is not suitable for indoor areas. It is highly suitable for highways and rural areas. This model employs less reflectors than the ray tracing model. In this case, we have two components at the receiver end.

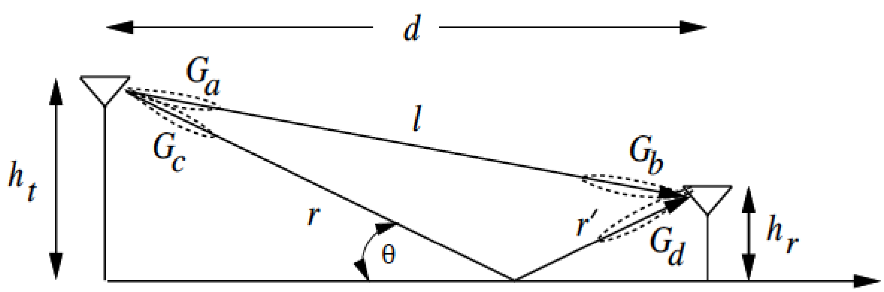

Figure 3.4: Two ray model [30]

One component is the received signal, and the other is the reflected version of the transmitted signal. The attenuation in (decibels) is given by

$$P_r(dBm) = P_t(dBm) + 10\log_{10}(G_l) + 20\ \log_{10}(\ h_t h_r) - 40\log_{10}(d)$$

P_r is the received signal power.

P_t is the transmitted signal power.

$G_l = G_a.G_b$ is the product of the field radiation patterns of the transmitting and receiving antennas in the LOS direction.

h_t is the transmitter height.

h_r is the receiver height.

d is the horizontal separation of the antennas.

3.4.1.1.5 Ten-Ray Model

In this model, we assume that the city is flat, with buildings on both sides of the street. When the street is modelled as a line of buildings, it can have an infinite number of reflections to the receiver end. However, most of the reflections may be weak because of the power dissipation [30].

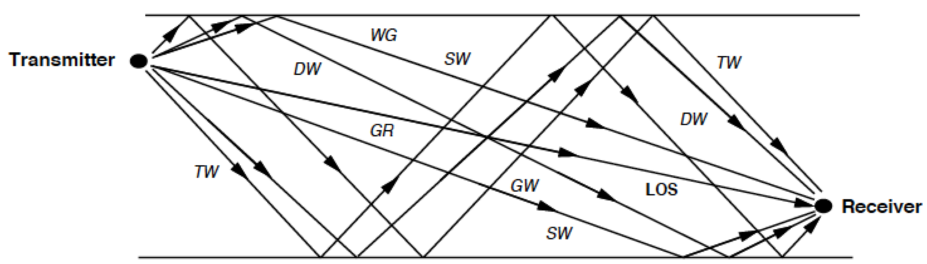

Figure 3.5: Ten ray model [30]

$$P_r = P_t\left(\frac{\lambda}{4\,\pi}\right)^2 \left|\frac{\sqrt{G_l}}{l} + \sum_{i=1}^{9} \frac{R_i\sqrt{G}_{xi}e^{j\Delta\emptyset_i}}{x_i}\right|^2 \quad [30]$$

P_r is the received power.

P_t is the transmitted power.

λ is the signal wavelength.

$\sqrt{G}_{xi}$ is the product of the gains of the transmitting and receiving antennas corresponding to the i^{th} ray.

l is the distance between transmit and receive antennas

R_i is the reflection coefficient.

x_i is the path length of the i^{th} reflected ray.

$$\Delta\phi_i = 2\pi(x_i - l)/\lambda$$

3.4.1.2 Shadow Fading

In the signal path, there can be random attenuation due to the blockage of objects. A model is needed for overcoming the effects of random blockages and attenuation.

Statistical models are mostly used, as the transformations in the reflecting periphery and scattering entities tend to vary randomly. One common model is lognormal shadowing. The important parameter in lognormal shadowing is the average path loss in decibels, i.e., $\mu_{\psi dB}$ [30] [36].

$$\mathrm{P}(\psi_{dB}) = \frac{1}{\sqrt{2\pi}\sigma_{\psi_{dB}}} exp\left[-\frac{(\psi_{dB}-\mu_{\psi_{dB}})^2}{2\sigma^2_{\psi_{dB}}}\right] \quad [30]$$

$\mathrm{P}(\psi_{dB})$ Average path loss in dB

ψ_{dB} Linear average path loss in dB

Here, μ is the mean, and σ is the standard deviation.

3.4.2 Data Link Layer

The data link layer is responsible for bit-error detection and re-transmissions. The MAC design is done in this layer. MAC determines the power and bandwidth allocation for the node to access the medium. The MAC design directly affects the performance and the QoS of the wireless network. The DCF and PCF are the two channel-accessing mechanisms in IEEE 802.11.

3.4.2.1 IEEE 802.11n

IEEE 802.11n works at both 2.4 and 5 GHz. It employs MIMO OFDM technology with a spatial stream of four channels. It uses multiple antennas to increase the data rates. It is appropriate for IEEE 802.11a and IEEE 802.11b users. Its net data rate ranges from 54 to 600 Mbps. IEEE 802.11n instigates MAC aggregation.

Small packets are clustered to form a bigger frame. As a result, less time is needed to content the channel, and reducing the total number of frames. Thus, the throughput is increased. The acknowledgement is not per frame but for a group of frames. This type of block acknowledgment is more appropriate for real-time applications, such as video and voice. IEEE 802.11n is popular owing to the capability of carrying real-time applications such as video. With the help of MIMO technology, high-definition (HD) signals can be reliably sent using video compression techniques such as H.264 and MPEG4. The predominant standard in the WLAN space is IEEE 802.11n, as it can generally by achieved by most devices, such as laptops and smartphones. The wireless routers in houses are equipped with the same technology [37].

3.4.2.1.1 DCF

DCF is the basic access scheme and utilises a CSMA with collision avoidance (CSMA/CA) mechanism. Here, the stations must contend for access to the channel, and there is no central controller. CSMA/CA uses imperative physical and arbitrary virtual carrier-sensing techniques. It observes the channel strength via physical carrier sensing. The virtual carrier sensing checks the availability of a channel by using the RTS/CTS handshake to allot the channel before sending the data.

3.4.2.2 IEEE 802.11ac

With the advancements in technology, the number of devices—e.g., sensors, robots, and controllers—that are unsuitable with LTE networks because of their higher energy consumption will be large in the near future. The existing WiFi is limited to a small number of devices and a short distance. It uses a 5-GHz frequency range that provides extended-range networks. It supports the simultaneous streaming of HD videos, backing up of large files, and wireless display. IEEE 802.11ac is an extension of the wireless networking protocol IEEE 802.11 that can be used for more MIMO spatial streams than IEEE 802.11n. In addition to the 40-MHz channel of 802.11n, there are 80- and 160-MHz channels. A multi-user version of MIMO is defined. Beam forming transmission can be used to extend the range and link reliability [38] .

3.4.2.3 LTE

LTE is designed for packet-switching services. It maintains IP integration between the user and the packet data network (PDN). It is based on the Universal Mobile Telecommunications Service (UMTS) and GSM technologies. UMTS uses wideband CDMA for radio access. The EPS network combines the radio aspect of LTE using the Universal Terrestrial Radio Access Network and the non-radio aspects using system architecture evolution (SAE). The EPS network architecture involves a core network (CN) and an access network.

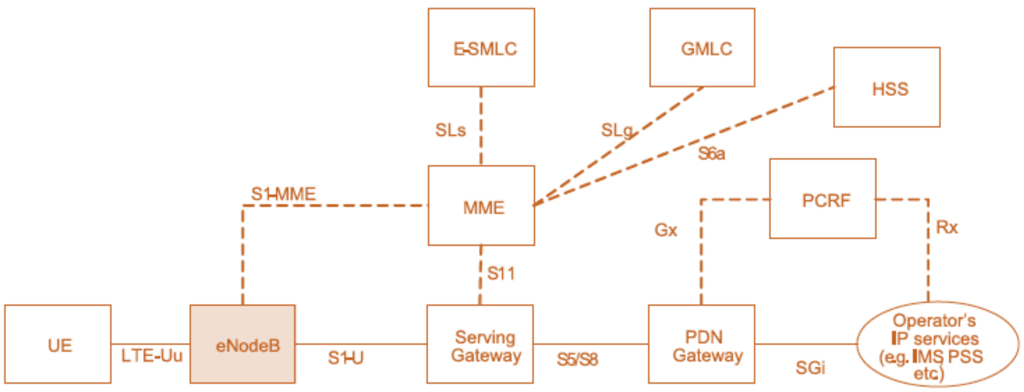

Figure 3.6: The EPS network overview [23]

3.4.2.3.1 Core Network

The CN regulates the user equipment and is authorised for directing calls and data. The QoS is authorised by the Policy and Charging Rules Function. It has the authority to make decisions regarding the policy control.

The Gateway Mobile Location Centre (GMLC) functionalities enable location services. The GMLC can determine the final location by sending positioning requests to the mobile management identity (MME). A home subscriber server

(HSS) contains information about restrictions for roaming. It also contains the SAE subscription data for the user. The MME can be accessed by the HSS. Each UE is allocated a specific IP address by the PDN gateway (P-GW). According to the different QoS bearers, the downlink IP packets are filtered by the P-GW. This is the block that connects to the outside world. When the UE falls into the sleep mode or the idle state, the serving gateway (S-GW) maintains the information about the data bearers. It also records the volume of data sent or received. The signalling between the UE and CN is achieved through the MME. The MAC layer of the LTE connects the logical channel and the transport channel via multiplexing and de multiplexing. It also consists of a hybrid automatic repeat request (HARQ), which is responsible for HARQ operations [23].

The purpose of the HARQ in LTE is to ensure high data rates. HARQ is also helpful for correcting error packets in the physical layer. Even though HARQ works in the physical layer, the MAC layer controls it. If there are errors in the information received, buffering occurs, and the sender is requested to retransmit. Once the data are retransmitted, they are joined with the buffered data before error detection and channel decoding. Thus, the retransmissions can improve the accomplishment [23].

3.4.3 Network Layer

The network layer deals with congestion control and IP addressing. An IP address is the identity of the source and the router network and is usually 32-bit. There is a physical point of contact between the host and the router. There is usually more than one interface for routers. The host may have a wired or wireless interface. The IP address is hierarchical not portable. The IP address cannot be used in multiple locations without a well-defined mechanism.

3.4.4 Transport Layer

In the transport layers, messages are either segmented or reassembled. Multiplexing is possible. Generally, there are two protocols in the transport layer: TCP and the User Datagram Protocol (UDP).

3.4.4.1 UDP

UDP is a best-effort datagram service. The IP services are distributed using multiplexing. The transmitter and receiver for UDP are easily managed. The service is not connection-oriented; thus, there is no need for handshaking. TCP has a larger header overhead than UDP. In UDP, there are no techniques to control the flow, errors, or congestion, and the packets may not follow a pattern. The delay is smaller than that in TCP. The applications are multimedia (e.g., voice, video, real-time transport protocol) and network services (e.g., domain name server, Routing Information Protocol, Simple Network Management Protocol). Considering these factors, we use UDP in our proposed network.

3.5 Energy Model

The total energy consumption is calculated by modelling the energy usage of the device during operation. The energy model considers a four-state radio interface: transmitting packets, receiving packets, sleep mode, and idle mode. Wireless-sensor nodes have different modules, e.g., microcontrollers, transceivers, sensors, and power-supply modules. The energy models are analysed for each module in different transition states.

3.5.1 Processor Energy Model

The processor supports three operation stages: sleep, idle and run. It is responsible for data processing and sensor control. The energy consumed by the processor is the sum of the total energy consumed in one state and the energy consumed during the transition from one state to another [39].

$$E_{processor} = E_{state} + E_{transition} = \sum_{i=1}^{m} P_{processor\ at\ state\ i} \cdot T_{processor\ at\ state\ i} + \sum_{j=1}^{n} N_{transition\ j} e_{transition\ j}$$

$P_{processor\ at\ state\ i}$ is the power of state i.

$T_{processor\ at\ state\ i}$ is the time spent in state i.

$N_{transition\ at\ state\ j}$ is the frequency of the state transition to j.

$e_{transition\ at\ state\ j}$ is the energy consumption of one state transition to j.

3.5.2 Transceiver Energy Model

The transceiver module is responsible for sending and receiving the data. The transceiver has six states (transmitting, receiving, sleep, idle, off, channel detection state (CCA/ED). The transceiver energy consumption is considered to be the sum of the energy consumed in one state and the energy consumed during the transition from one state to another.

$$E_{transceiver} = E_{tx} + E_{rx} + E_{idle} + E_{sleep} + E_{off} + E_{CCA}$$

$$= \sum_{i=1}^{N_{tx}} P_{tx} L_i / R + \sum_{i=1}^{N_{rx}} P_{rx} L_i / R + P_{idle} T_{idle} + P_{sleep} T_{sleep} + P_{CCA} T_{CCA}$$

$$= \sum_{i=1}^{N_{tx}} V_{tr} I_{tx} L_i / R + \sum_{i=1}^{N_{rx}} V_{rx} I_{rx} L_i / R + V_{tr}(I_{idle} T_{idle} + I_{sleep} T_{sleep}$$

$$+ I_{CCA} T_{CCA})$$

E_x is the energy consumption in state x.

P_x is the power in state x.

I_x is the current in state x.

T_x is the time interval in state x.

V_{tr} is the working voltage.

L_i is the size of the i^{th} transmitted or received packet.

R is the transmission speed.

N_{tx} and N_{rx} are the total numbers of packets sent and received, respectively [39].

3.5.3 Sensor Energy Model

The sensor module is responsible for data collection and digital conversion. It also performs signal sampling and signal modulation. The sensor functions in either the periodic mode or the burst mode. In the periodic mode, the sensors toggle between the ON and OFF states.

$$E_{ensor} = E_{on-off} + E_{off-on} + E_{sensor-run} = N(e_{on-off} + e_{off-on} + V_s I_s T_s)$$

$E_{on\text{-}off}$ is the energy consumption for the closing operation.

$E_{off\text{-}on}$ is the energy consumption for the opening operation.

$E_{sensor\text{-}run}$ is the energy consumption for the sensing operation.

V_s is the working voltage of the sensor.

I_s is the current of the sensor.

T_s is the time interval of sensor operation.

N is the number of sensor opening and closing operations [39].

Chapter 4: Simulation Model and Performance Results

4.1 Introduction

In this chapter, our proposed network structure for smart cities is studied and evaluated using computer simulations. First, the simulation assumptions and procedures are explained in detail. After that, the simulation results are introduced and discussed.

4.2 Simulation Model Description

The NS2 simulator is used for simulation. NS2 is an open source discrete event packet level simulator. NS2 can be used to simulate wired and wireless network functions and protocols.

Consider a flat grid topology with an area of 100 X 100 m. The smart city sensor nodes are assumed uniformly distributed over this area. These nodes are classified into low priority (lpnn) and high priority nodes. In fact, high priority nodes can perform the real time applications like CCTVs, health-monitoring systems, and emergency notifications on roads. On the other hand, low power sensors like temperature sensors, motion detectors, can be considered as low priority nodes. Different possible application traffic rates (referred to hereafter as source rates) for high priority and low priority nodes (lpnn) are considered in our simulation. Different LTE and WiFi transmission rates are considered and evaluated.

Based on our proposed network structure, each node has two wireless interfaces. One is connected to a WiFi access point, whereas the other is connected to an LTE base station (eNodeB). The information generated by smart city sensors is supposed to be sent to their data collection servers via a backbone network that is connected to the WiFi access points and the core LTE network.

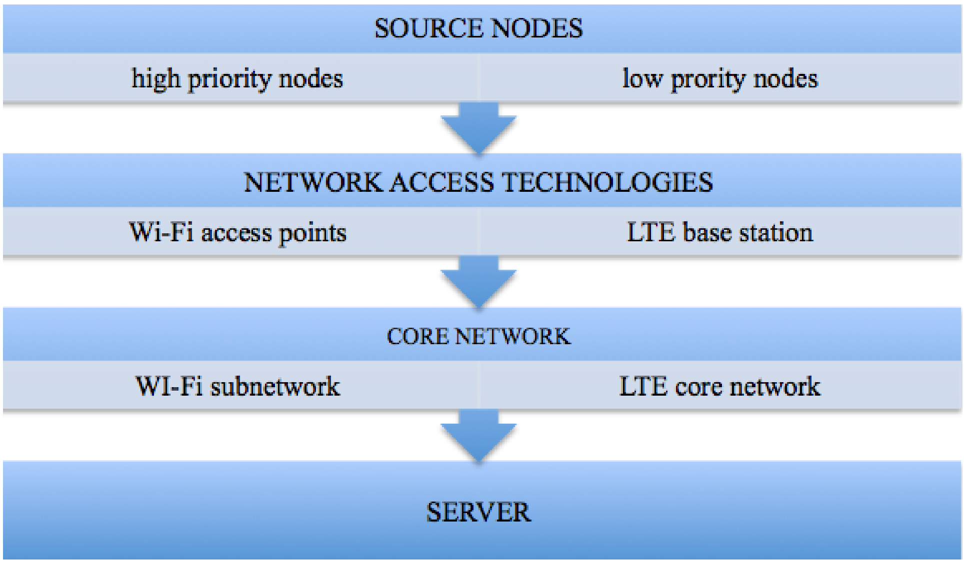

Figure 4.1: Data flow in the proposed simulation model topology

In the simulation, the Two-ray Ground propagation model is used unless otherwise is mentioned. For comparison purposes, other models such as Free Space and Shadowing are considered. Two MAC protocols are used. IEEE 802.11 is used for WiFi, whereas a contention-free MAC emulates the LTE connection. The ns-2 simulator nodes are modified in such a way that lets a node to communicate over both interfaces simultaneously using the user datagram protocol (UDP). The packets from traffic source are distributed equally on both interfaces.

The interface queue type used is drop-tail that means when the number of packets exceeds the queue length, the last packet is dropped. The maximum number of packets is the interface queue is limited to 50 packets. The antenna type used is Omni.

Since the proposed network structure is based on single-hop communication, the routing protocol used is No Adhoc Routing Protocol (NOAH). NOAH is a wireless routing protocol that supports direct communication between wireless nodes and base stations. Generally there are no routing related packets send from NOAH. The physical parameters and MAC parameters used in the simulation are summarized in Table 4.1 and Table 4.2 below, respectively.

Physical layer Parameters	Settings
Antenna model	Omni antenna
Interface queue	Drop-tail
Packet size	1000 bytes
Transmission interval	8ms
Initial energy	50 J
Routing protocol	NOAH
Topography	Flat grid

Table 4.1: Physical layer parameters

MAC layer Parameters	Settings
Data rate for WiFi	36, 54, 65, 104, 130 Mbps
Data rate for LTE	1.75-3.25 Mbps* * Varies for the number of nodes
Source rate	250, 300, 350, 400 Kbps
Maximum number of packets in IFQ	50
MAC for WiFi	802.11 (WiFi), Modified simple (LTE)

Table 4.2: MAC layer parameters

4.2.1 Simulation Assumptions and Considerations

The following assumptions have been followed in all performed simulations:

1) The nodes are distributed in a 100 X 100 m area
2) Simulated wireless nodes are either source nodes or sinks. We assume that both source and sink nodes have same characteristics in terms of power consumption.
3) The simulation time is chosen to be 50 seconds
4) For the sake of simplicity, we have assumed the links between nodes are symmetric and have the same bandwidth.

We study the performance of our proposed network structure for different smart city applications in terms of packet delay, packet loss and energy consumption.

Each experiment is repeated 50 times with different distribution of nodes. The source rate for high priority nodes have been selected based on the application rates those are used in smart cities. We consider CCTV source rate of 250 Kbps. It is the minimum acceptable rate to identify human faces under certain experiment done in London in a bus to identify the passengers. A low priority node source rate (lpnn) is chosen based on low data rate sensory applications such as smart parking, in which a packet data of 50 bytes are sent every 15ms [40] [41].

4.2.1.1 Energy Model

As one of our main concerns is the energy consumption of multi homed smart city sensors, we follow the energy model shown in figure 4.2 to characterize the energy consumption of the WiFi interface. In this mode, the power consumed by the

WiFi node during transmission is approximately 1258mW and in the idle state is 884mW [42].

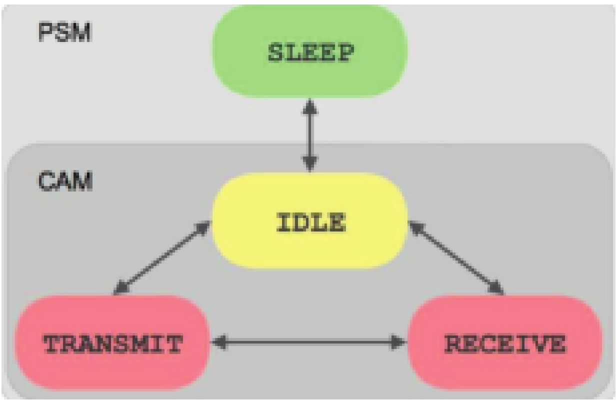

Figure 4.2: WiFi energy states and possible transitions [42]

As shown in figure 4.2, during data communication, the idle state is switched to transmit state. Therefore, the net power used for transmission, is 374mW.

Similarly the receiving node power consumption is 1181mW, and hence the power that is used for reception is 297mW [42].

For the LTE energy measurements, we follow the model introduced in [42]. We assume the peak rate of LTE in the uplink is 75Mbps. The model in [40] relates the power consumption with the interface throughput based on the following equation

$$P_u = \alpha_u . t_u + \beta \quad [40]$$

where P_u is the transmit power of the uplink, α_u= 438.39mW/Mbps,

t_u is the link throughput, and β is a constant equal to 1288.04mW.

For LTE links, maximum throughput per node can reach the peak data rate provided the entire bandwidth is allocated to one node only. Assuming an LTE eNodeB running weighted fair queuing scheduling algorithm, the peak LTE channel rate is almost divided evenly among all the nodes. For instance, if 40 nodes exist in one LTE cell, the LTE rate per node is around 1.75 Mbps. If this value is substituted in the above equation, the transmit power can be calculated as 2.06 Watts.

4.3 Proposed Network Structure Performance Comparison

In order to evaluate the benefit of the proposed network structure, a comparative performance study is done between the proposed network, a single interface LTE-based network, and a single-interface WiFi-based network for smart city applications. The experiment is conducted to observe the packet delay, packet loss and energy consumption in the three different networks.

4.3.1 The Effect of Number of Nodes

In this analysis, the low priority nodes are distributed as 40% of the total nodes. The high priority nodes are varied. The WiFi rate is fixed at 54 Mbps and LTE rate at 1.75 Mbps. The source rate is fixed at 250 kbps and the low priority source rate at 20 Kbps. The effect on packet delay, packet loss and energy consumption is tested as in the following.

4.3.1.1 Packet Delay

As figure 4.3 reveals, the delay in the multi homed network structure is more compared with LTE-based network in each set of nodes. The LTE-based network can achieve a lower delay compared with WiFi and multi homing structure since it does not suffer from packet collisions as in the case of WiFi. In WiFi the bandwidth is shared among all the nodes, and hence, the more the number of nodes the less the rate that each node achieves. Indeed, the proposed multi-homing network is affected by the packet collisions and medium sharing over the WiFi interface, which leads to a higher delay compared with LTE-based networks.

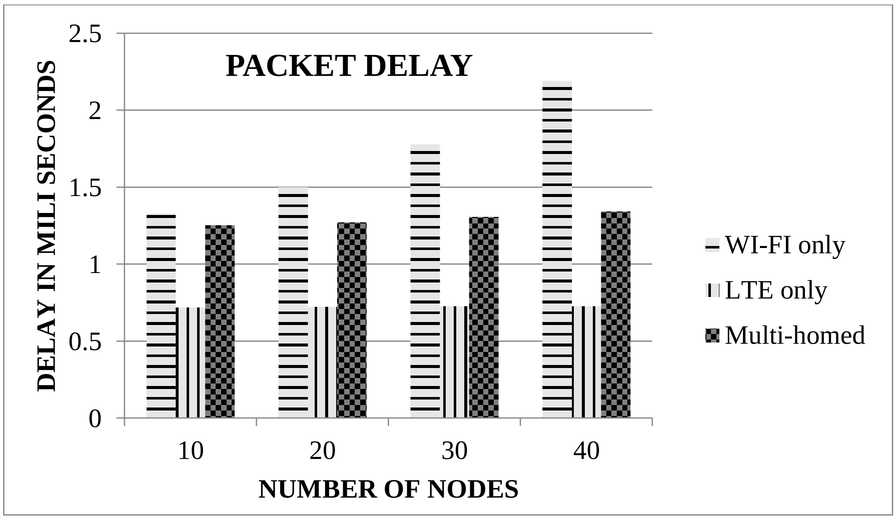

Figure 4.3: Packet delay comparison for different network types

4.3.1.2 Packet Loss Percentage

Figure 4.4 demonstrates that the packet loss is negligibly small in WiFi. Multi-homing network structure behaves more like LTE-based network observed in figure 4.4 In fact, as observed also in other experiments, the main contributor of packet loss in the multi-homing network is the LTE interface not the WiFi one. In an LTE network, when more nodes are use the channel, the total rate of the cell is divided between them, which it may make the source rate exceed the capacity of channel. This leads to long queues and possibly retransmissions. After a number of retransmissions, packets are dropped, which results in high packet loss. In WiFi the bandwidth is shared among the nodes, the more the number of nodes the less the rate that each node achieves. This may lead to a queue build up, which leads to packet overflow.

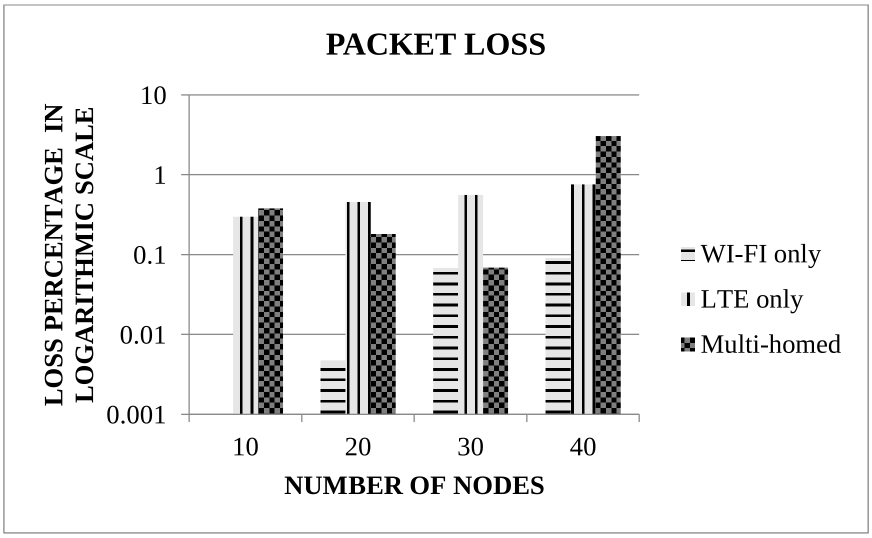

Figure 4.4: Packet loss percentage for different networks

4.3.1.3 Energy Consumption Performance with Different Number of Nodes

In this section, the energy consumption in the proposed multi homing network structure is compared with a WiFi-based network and an LTE-based network. The initial energy value used is 50 Joules. The WiFi-based network transmission rate is 54 Mbps, the source rate is 250 kbps, and low priority source rate is 20 kbps. The low priority nodes are distributed at 40% of the total nodes. As depicted in figure 4.5, the energy consumption in the multi-homed network structure is low compared with the WiFi-based network. In multi-homed network, the energy consumption is in the range of 2 to 7 joules where as for the WiFi based network it is between 5 to 22 Joules. The reason is that the multi-homed network structure shares the total traffic load between the WiFi and the LTE interface. For WiFi based network, the nodes are sharing the same bandwidth. Consequently, increasing the number of nodes leads to a higher probability of packet collisions. This, in turn, leads to an increase in the number of retransmissions, which eventually result in higher energy consumption.

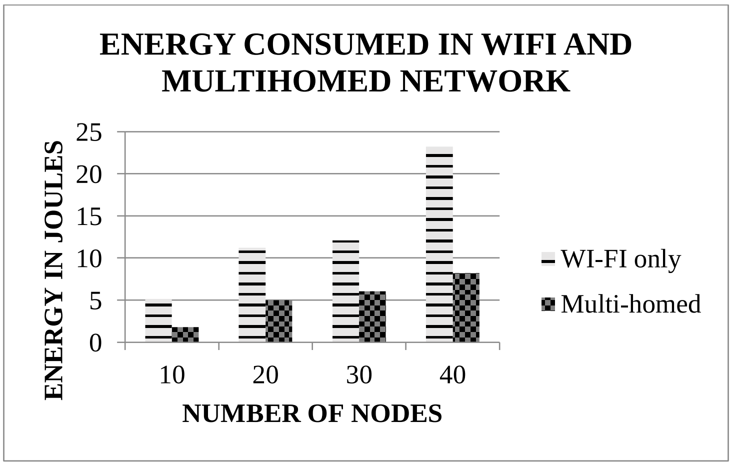

Figure 4.5: Energy consumed in WiFi-based and multi-homed network

Next, the energy consumption of the proposed multi-homed network structure is compared with an LTE-based network. The LTE-based network transmission rate is 1.75 Mbps, the source rate is 250 kbps, and low priority source rate is 20 kbps. The low priority nodes are distributed at 40% of the total nodes. In the multi-homed network, the energy consumption is in the range of 2 to 9 joules whereas for the LTE-based network it is between 4 to 12 Joules. Apparently, distributing the traffic load between the LTE and WiFi interface reduces the amount of traffic on the LTE interface, which, in turn, reduces the energy consumed.

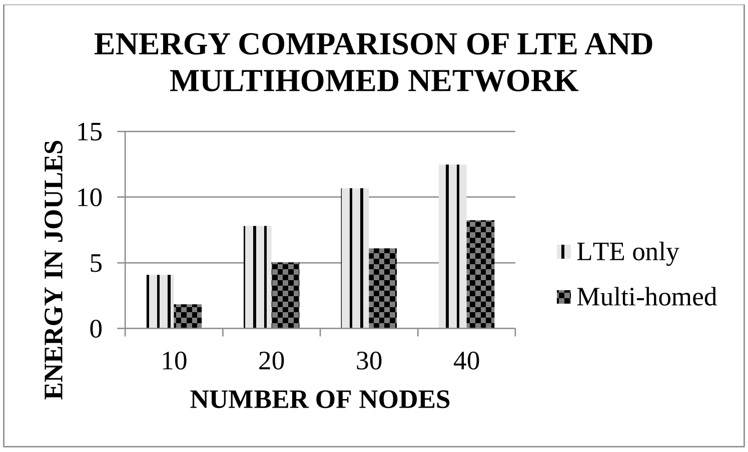

Figure 4.6: Energy consumed in LTE-based network and multi-homed network

4.3.2 The Effect of High Priority Source Rate

In this section, a performance comparison is conducted between a WiFi-based network, an LTE-based network, and the proposed multi-homed network structure focusing on the effect of different high priority source rates. The numbers of high priority nodes is 20 and the low priority nodes are distributed as 40% of the high priority nodes. The LTE rate is 3.25 Mbps. The WiFi network transmission rate is 54 Mbps. The low priority source rate is 20kbps. The high priority source rate is varied.

4.3.2.1 Packet Delay

As figure 4.7 reveals, the delay is higher in a WiFi based network compared with both an LTE based network and multi homed networks. Moreover, the multi homed network experiences the lowest packet delay. Although, there is no contention in an LTE-based network, the higher capacity provided by the two interfaces in the multi-homed network provides a shorter packet delay. In a WiFi-based network, when source rate increases, the packet collision probability also increases leading to large packet delay due to retransmissions.

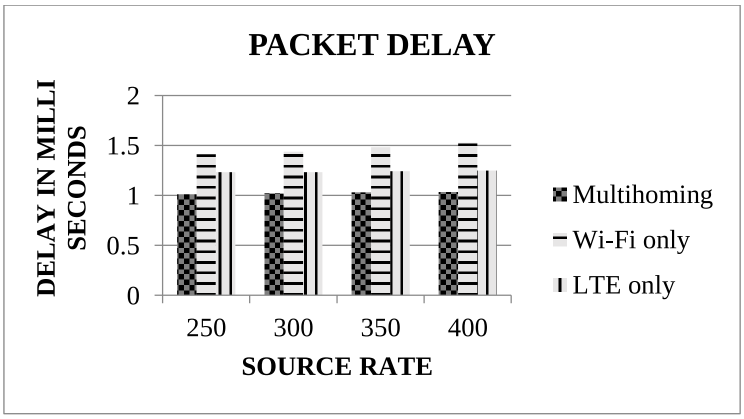

Figure 4.7: Packet delay in LTE-based, WiFi-based and multi-homed network with different source rates

4.3.2.2 Packet Loss

Our study reveals that the packet loss increases in WiFi-base, LTE-based, and the proposed multi homing structure with increasing the source rate. This is anticipated since a larger number of packets are transmitted with the same data rate of the channel. This may cause some packets dropped out of the network queues, and hence reach the management server. In an LTE-based network, when the source rate exceeds the data rate provided by the channel, a buffer overflow occurs, which leads to packet loss. In a WiFi-based network, when source rate increases, larger amount of data packets share the channel, which results in higher collision probability and longer packet service time. This decreases the effective available channel rate, and hence leads to a possible overflow condition. However, the loss is negligible in a WiFi-based network compared to an LTE-based network and the proposed multi homing network structure as revealed in figure 4.8. The reason for this trait is the low rate available per node for an LTE-based network and also the low available rate of the LTE interface in the proposed network structure. As observed in other conducted experiments, the main contributor of packet loss in the proposed multi-homing network is LTE interface rather than the WiFi interface.

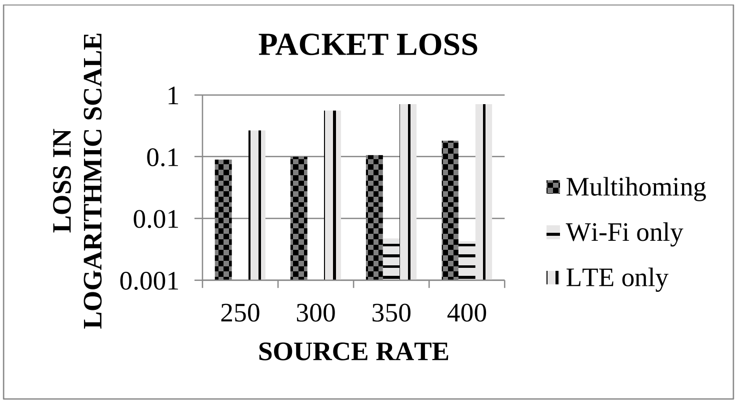

Figure 4.8: Packet loss in LTE-based, WiFi-based and multi-homed network with different source rate

4.3.2.3 Energy Consumption Comparison

First, we compare the energy consumption of a WiFi-based network with the energy consumed in the proposed network structure. The WiFi channel rate is 54 Mbps. The numbers of nodes is fixed at 20 and the low priority nodes are attributed to 40% of the total nodes. The low priority source rate is 20 Kbps. The energy consumption in the multi homed network is very low compared to the WiFi network as revealed in figure 4.9. This is because in multi-homed network the total load is shared between WiFi interface and the LTE interface, and hence less number of packets is sent over each. However, for the case of WiFi-based networks, the nodes share the same bandwidth, and hence high traffic rate causes packet collisions which leads to retransmissions.

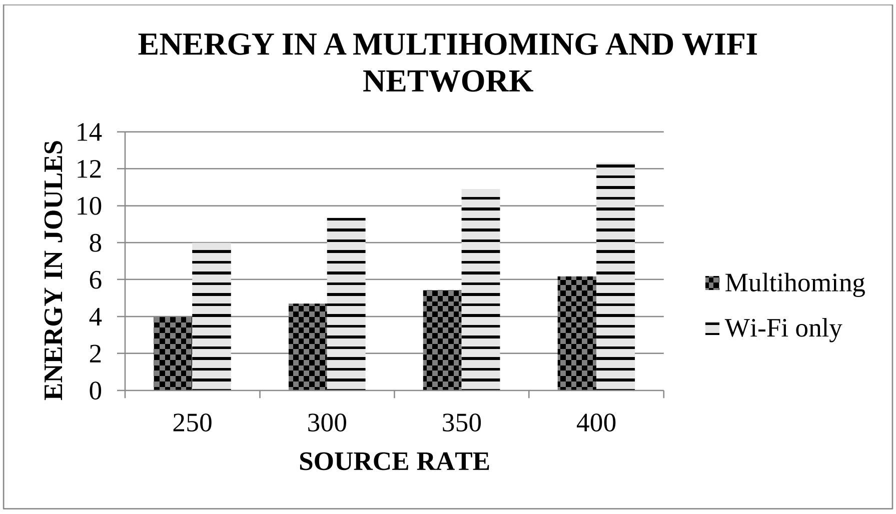

Figure 4.9: Energy consumption of WiFi-based network and multi-homed network with different source rates

Second, we compare the energy consumption of an LTE-based network with the proposed multi-homed network structure. The energy consumption in the multi-homed network is less compared to the LTE-based network as can be observed from figure 4.10. In the LTE-based network, the uplink rate is distributed among different network nodes. This makes the rate obtained by each node is low, which leads to a large energy consumption, especially when the source traffic rate increases.

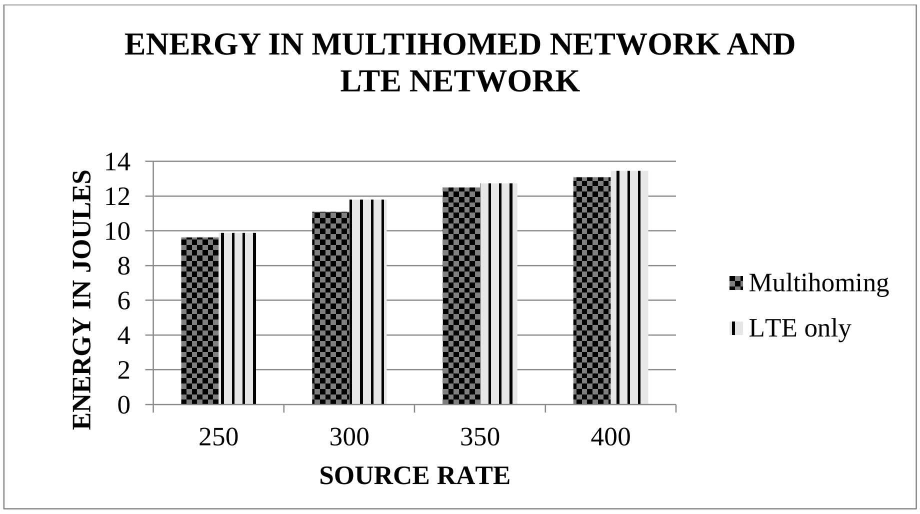

Figure 4.10: Energy Consumption of LTE-based network and multi-homed network with different source rates

4.4 Performance Study of the Proposed Network Structure

In this section, a comprehensive simulation study of the proposed network structure is presented. The study is performed against the change of the main parameters that govern the packet transfer delay, packet loss and energy consumption. These parameters include the number of network nodes, the ratio between high and low priority nodes, the WiFi channel rate, the LTE channel rate, the application traffic rate, and the channel propagation model.

4.4.1 The Effect of Number of Nodes

In this case study, the source rate is fixed at 250 kbps and low priority source rate is fixed at 20 kbps. The WiFi channel rate is 54 Mbps and LTE rate is 1.75 Mbps per node. The number of high priority nodes is gradually increasing from 10 to 40 nodes. The ratios of the low priority nodes to high priority ones are varied.

4.4.1.1 Packet Delay

It is observed that the delay is negligible when the low priority nodes where 70% or 80% of the total nodes. This shows that when majority of nodes are running non-real time applications delay is very small. Also, the delay is almost the same (varying between 1.25 to 1.3ms as in figure 4.11) even when the number of nodes changed from 10 to 40 since the network resources are still underutilized.

When the number of low priority nodes represents 20% and 30% of the total nodes the delay is negligibly small when the total number of nodes is less than 20. However, the packet delay increases when the number of nodes is increasing. The reason is that the WiFi bandwidth is shared among the network nodes. Therefore, the more the number of nodes, the less the data rate that each node achieves. Consequently, this leads to having a large average queue length of each node in the network. In the LTE network, when large amount of nodes simultaneously occupy the data rate provided by the channel, large amount of data buffering occurs that may lead also to higher packet delays.

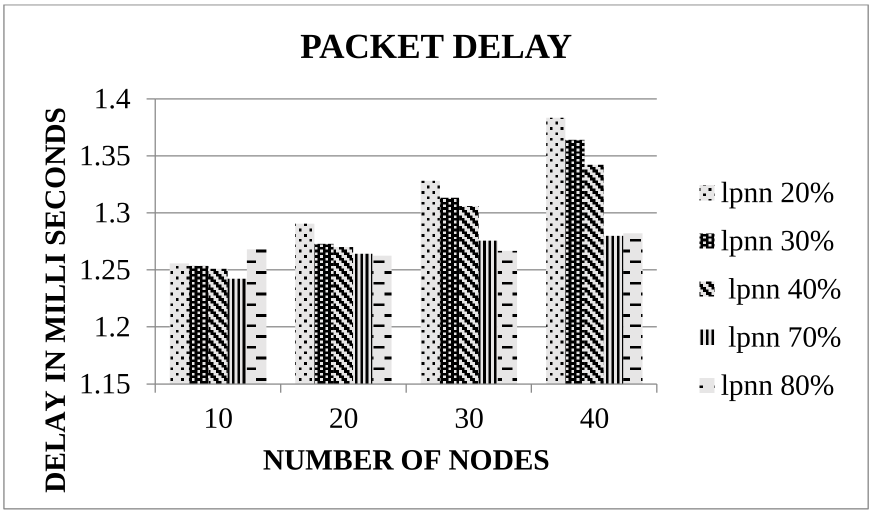

Figure 4.11: Delay time for the effect of number of nodes

4.4.1.2 Packet Loss

It can be observed from the figure 4.12 that there is almost no loss and most of the packets are received when the low priority nodes consume 70% and 80% of the total nodes. However, when the number of low priority nodes is 20% of the total number of nodes, the loss is in the range of 0 to 10% for the number of nodes up to 40. In case the number of low priority nodes is 30% and 40% of the total, the loss remains in the same range for the number of nodes less than 30. With low priority nodes acquire 40%, when the number of nodes are less than 30 most of the packets are received and the loss is almost zero. In the LTE network, when large amount of nodes simultaneously occupy the channel, large amount of data buffering occurs, which, may lead to buffer overflow. In the WiFi network, again, since the bandwidth is shared among the nodes, the more the number of nodes the less the date rate achieved by each node, which may also result in buffer overflow.

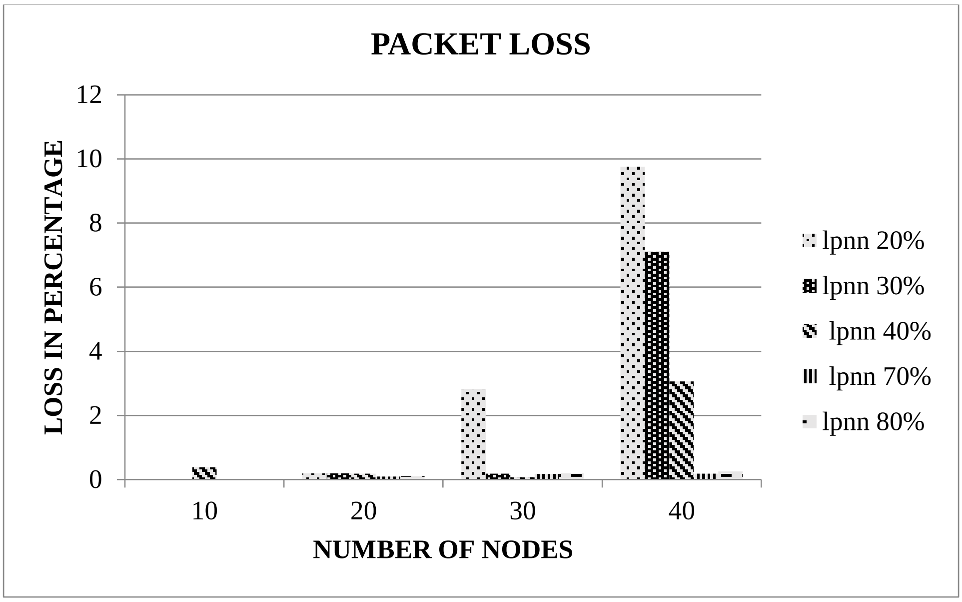

Figure 4.12: Packet loss for the effect of number of nodes

4.4.1.3 Energy Consumption in LTE And WiFi

4.4.1.3.1 Energy in LTE

The energy consumed is comparatively low when large numbers of low priority nodes exist, whereas in case there are large numbers of high priority nodes, the difference in energy consumed is slight. The LTE energy consumed is lower when the number of low priority nodes was 70 or 80% of the total number of nodes as shown in figure 4.13.

In case of the low priority node occupied 20, 30 or 40% of the total number if nodes the energy consumption is relatively higher since high priority nodes consume more energy. The amount of energy consumed per node is increasing with the increase in the number of nodes since data transmission over the LTE interface tends to take longer time.

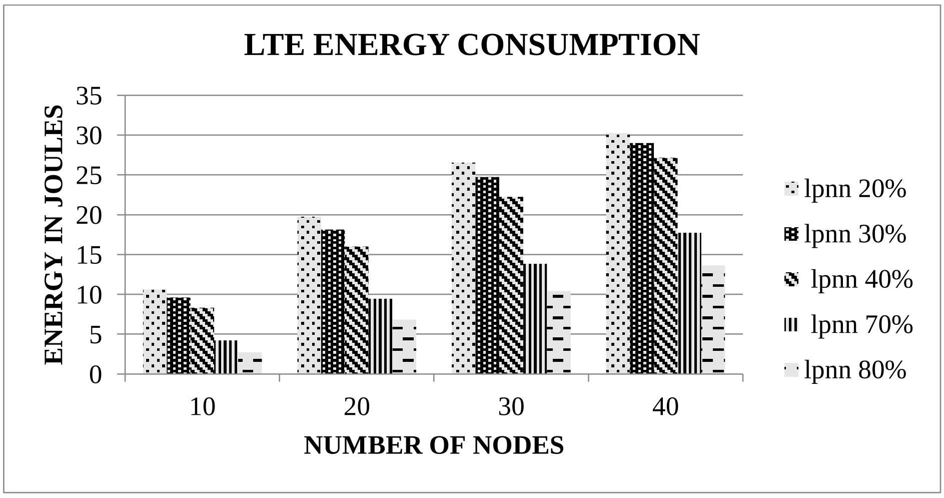

Figure 4.13: LTE energy consumption for the effect of number of nodes

4.4.1.3.2 Energy in WiFi

The energy consumed is comparatively low when the penetration of low priority nodes is higher. Generally, the WiFi interface energy consumption is high when the number of low priority nodes was only 20 or 30% of the total number of nodes since high priority nodes tend to send more packets, and hence consume more energy. Apparently, the amount of energy consumption of the WiFi interface increases with the increase in the number of nodes. For WiFi, the nodes are sharing the same bandwidth. When number of nodes increase, the same channel is shared among more users. This results in higher probability of packet collisions in the network, which, in turn, increases energy consumption. However the overall WiFi interface energy consumption is low compared with the energy consumption of the LTE interface share since the WiFi interface transmission rate (54 Mbps) is higher than the LTE interface rate (1.75 Mbps).

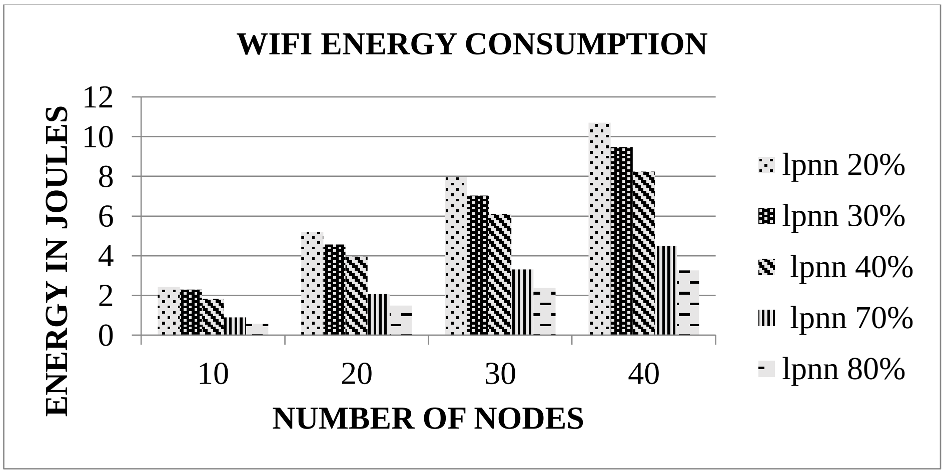

Figure 4.14: WiFi energy consumption for the effect of number of nodes

4.4.1.3.3 Energy in Multi-Homed Network

The energy consumption per node of the proposed network structure is the sum for both interfaces. Therefore, even when the number of low and high priority nodes changes the energy consumption for each interface stays the same.

The overall energy consumed in the proposed network structure increase when the number of nodes increases. Also, the amount of energy consumed is less when more numbers of nodes are low priority nodes because these devices tend to send lesser amount of packets. The overall amount of energy consumption per node increases as the number of nodes increases. As mentioned earlier, when the number of nodes increases, this results in higher probability of packet collisions in the network.

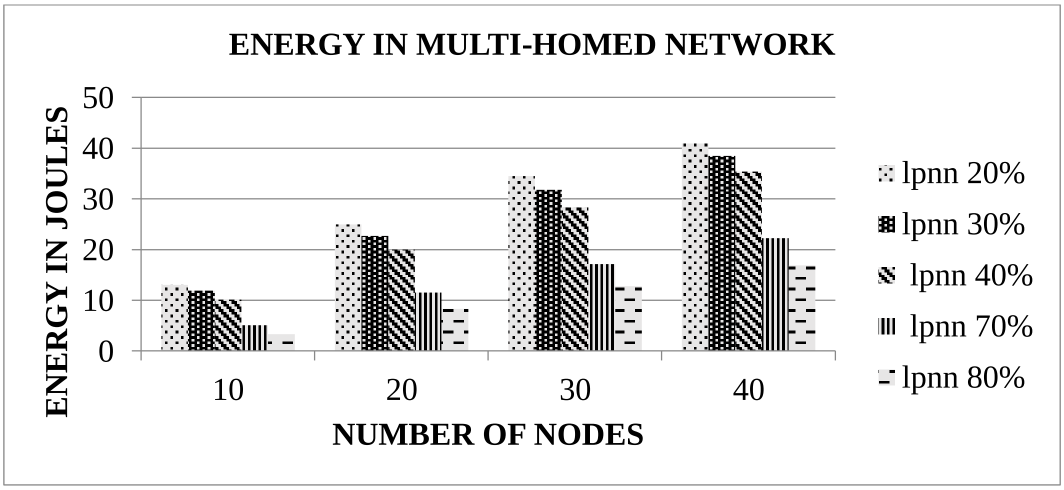

Figure 4.15: Energy consumption in multi-homed network for the effect of number of nodes

4.4.2 The Effect of Same Data Rate for WiFi and LTE

This experiment is performed to analyze a particular case in which the WiFi-interface and LTE-interface are assigned the same channel rate. In this simulation experiment, the WiFi and LTE interfaces are assigned a data rate of 6 Mbps. The high priority source rate is fixed at 250Kbps and the low priority source rate given is 20Kbps. The low priority nodes penetration is 50% of the total number of nodes.

4.4.2.1 Comparison of Energy Consumption of WiFi And LTE Interfaces

In each set of simulation experiments, it is clear from figure 4.16 that the LTE interfaces consume less energy than the WiFi counterpart. In WiFi network, while keeping the rate fixed at a particular value, any failed transmission due to packet collisions leads to a retransmissions, which in turn consumes more energy compared with the contention-free LTE interface.

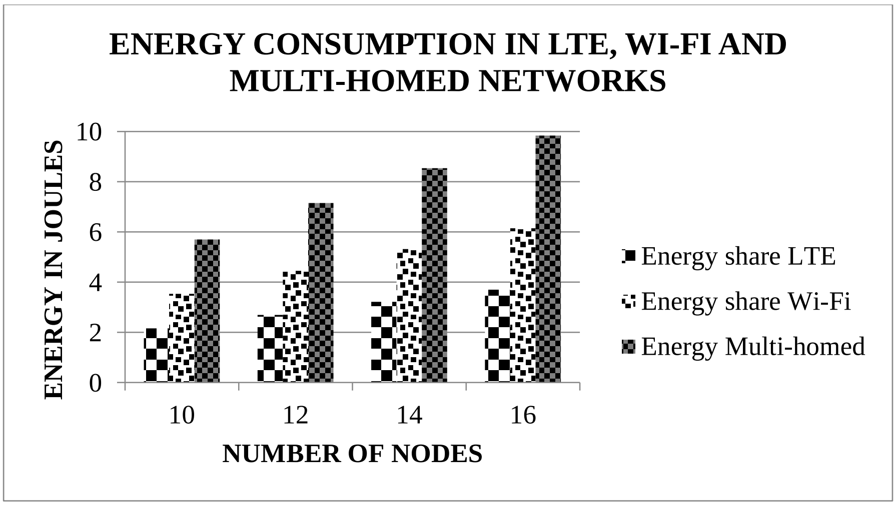

Figure 4.16: Energy consumption in WiFi and LTE provided with same data rate

4.4.3 The Effect of High Priority Source Rate

In this case study, low priority node source rate is fixed at 20Kbps. The WiFi channel rate is 54 Mbps and LTE rate is 1.75 Mbps per node. The number of nodes is fixed at 20 and low priority nodes constitute 40% of the total nodes.

4.4.3.1 Packet Delay

By increasing the source rate, the delay also increases as shown in figure 4.17. The maximum delay is less than 1.32ms. As it can be observed form figure 4.17, when the source rate is between 300 and 350Kbps, the delay increases slightly. However, the delay is lower than what is required for video streaming applications. Generally, when the source rate increases more packets are injected in the network; this leads to longer queues, and hence larger packet delays. Also, for the WiFi interface, in particular, this causes more packet collisions, which leads to an increased packet delay.

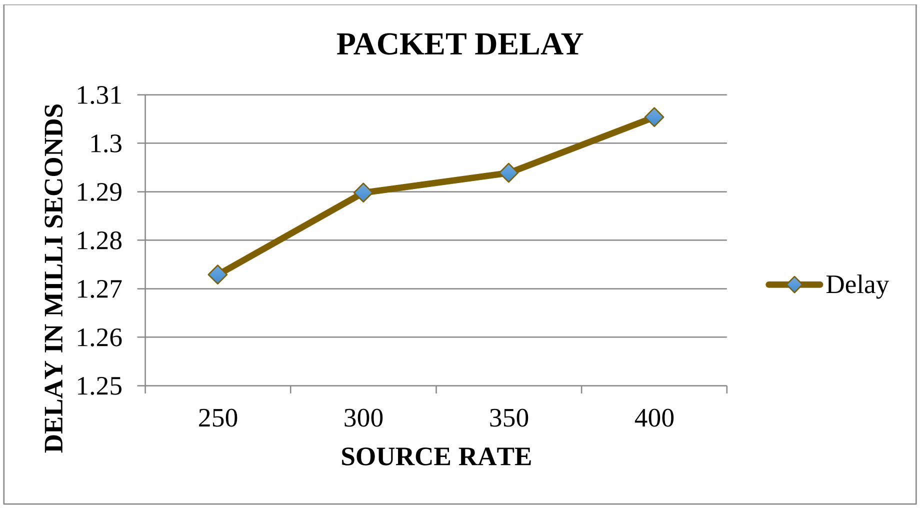

Figure 4.17: Delay time with the effect of high priority source rate

4.4.3.2 Packet Loss

Higher losses are observed with higher source rate. This is logical since more number of packets is getting transmitted with the same data rate of the channel. This may cause some packets not to reach in the server. The loss is around 1 % in case of 400 Kbps whereas for source rate is less the loss is less than 0.5%.

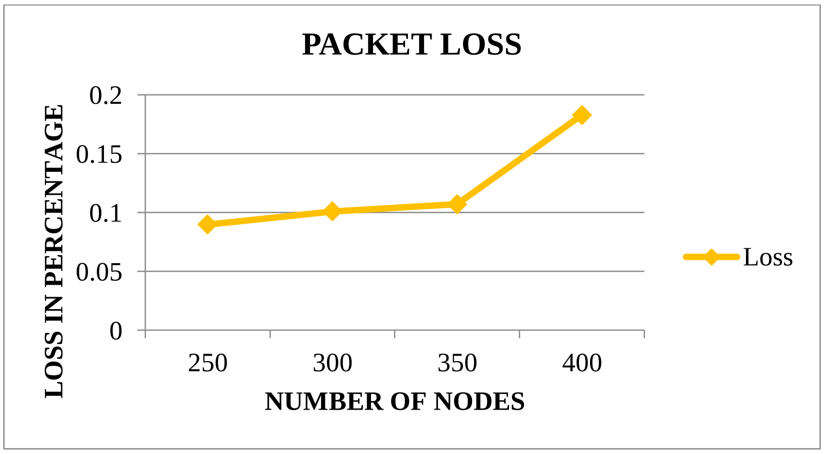

Figure 4.18: Loss percentage with the effect of high priority source rate

4.4.3.3 Energy Comparison in WiFi, LTE And Multi-homed Network

In general, the energy consumption is more in LTE than WiFi for the same set of parameters mentioned above. However, when the source rate increases the amounts of energy consumed in LTE and WiFi is proportionally increase. Figure 4.19 gives a clear picture that the energy consumed in WiFi is much less compared to LTE since the WiFi uses higher channel rate. This makes most of the energy consumption of the proposed structure comes from the LTE interface. The WiFi interface energy consumption increases naturally by increasing the data rate due to an increase of packet collision probability.

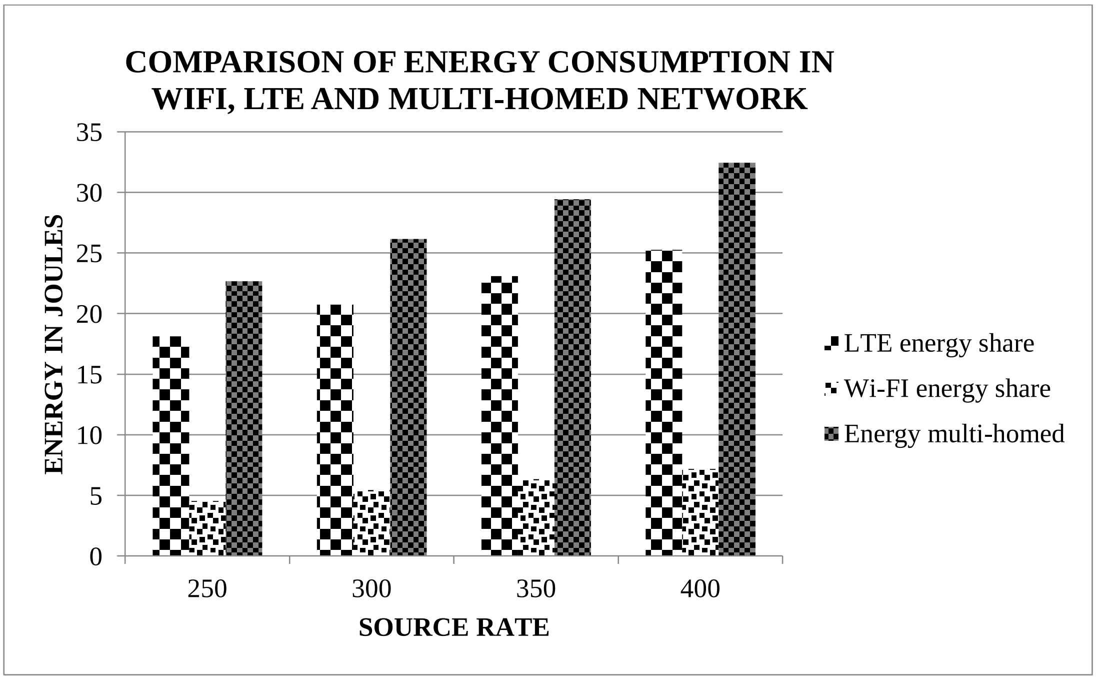

Figure 4.19: Energy consumption in LTE interface, WiFi interface and the proposed multi-homed network with the effect of high priority source rate

4.4.4 The Effect of Low Priority Source Rate

In this study, high priority source rate is fixed at 250Kbps. The WiFi channel rate is 54 Mbps and LTE rate is 3.25 Mbps per node. The number of nodes is fixed at 20 and low priority nodes constitute 60% of the total number nodes.

4.4.4.1 Packet Delay

Unlike the high priority source rate, the change in packet delay when changing the low priority source rate is negligible as can be observed from the figure 4.20. The packet delay increased very slightly when increasing the low priority source rates to almost doubles its value. This is mainly due to the fact that the low priority nodes are not contributing a larger number of packets to the network.

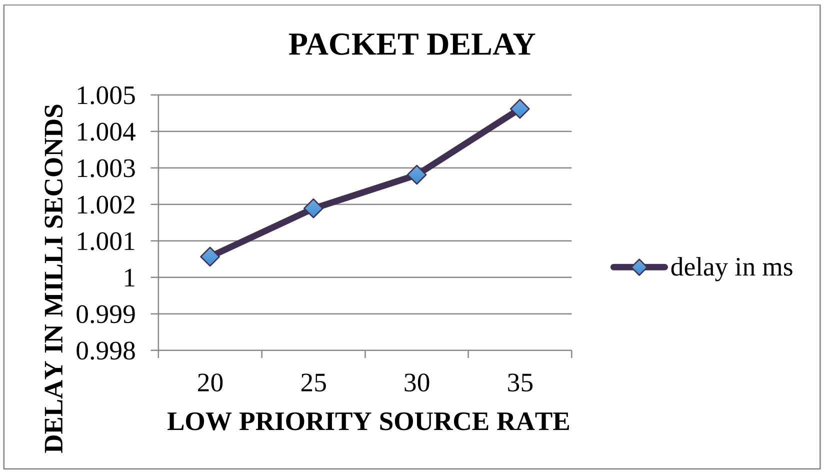

Figure 4.20: Packet delay with different low priority source rates

4.4.4.2 Packet Loss

The change in packet loss is also marginal when changing the low priority source rate as can be observed from the figure 4.21. The range of packet loss in this case is from 0.02 to 0.18%. Compared with high priority source rate effect, the low priority source rate does not affect the performance of the proposed network structure since low priority nodes do not load the network as high priority ones.

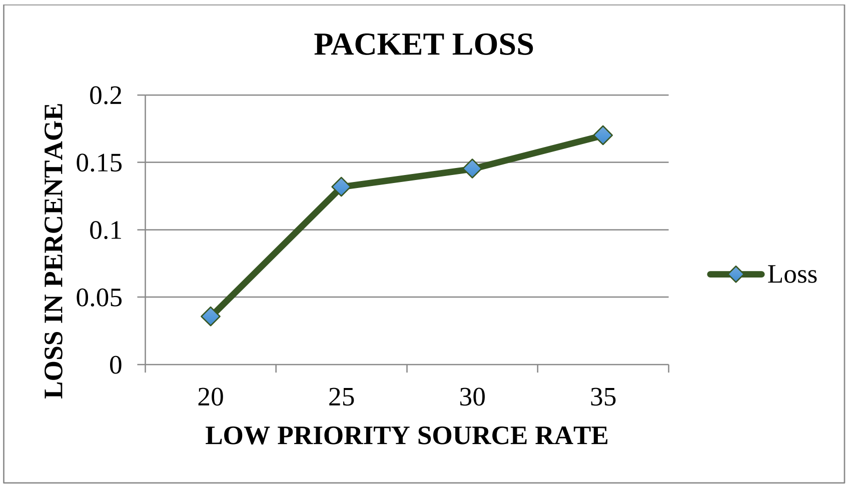

Figure 4.21: Packet loss with different low priority source rates

4.4.4.3 Energy Comparison in WiFi, LTE and Multi-homed Network

The energy consumption in both LTE and WiFi almost remains constant with increasing the low priority source rate. This is expected as low priority sources do not send large number of packets generally compared with high priority ones leading to small effect on consumed energy of the proposed network structure.

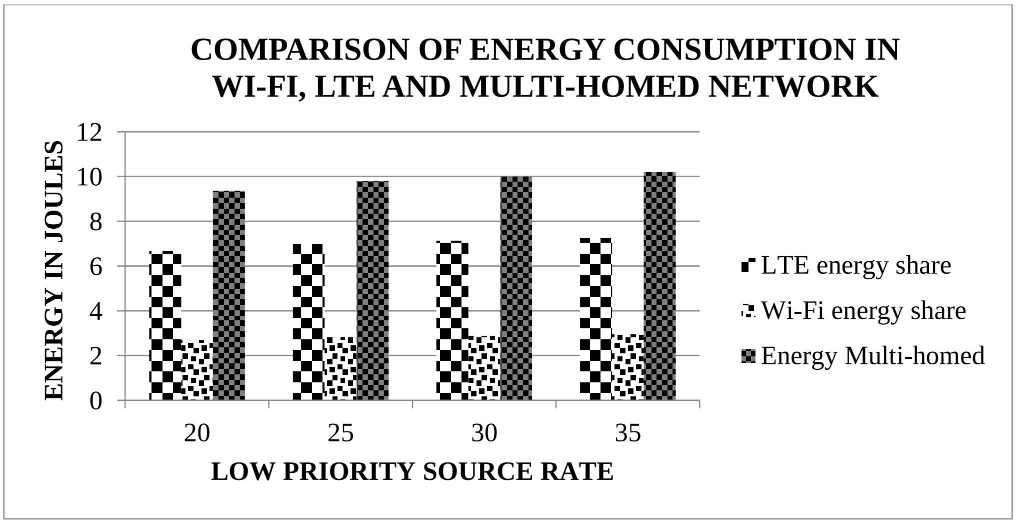

Figure 4.22: Energy consumption in LTE interface, WiFi interface and the proposed multi-homed network with different low priority source rates

4.4.5 The Effect of LTE Data Rate

Release 8 LTE data rates are considered as a worst-case scenario. The throughput of the uplink is 75 Mbps. The number of low priority node represents 40% of the total nodes. The source rate is 250kbps and low priority source rate is 20 kbps. The WiFi channel rate is fixed at 54 Mbps [26].

4.4.5.1 Packet Delay

As the LTE data rate increases with traffic source rate unchanged, a better performance of the proposed network is observed. As can be depicted from the figure 4.14, the packet delay decreases with increasing the LTE rate. The delay is decreased from 1.3ms to 1ms (around 25%) when the LTE rate is increased from 1.75 to 3.25 Mbps (nearly doubled). However, increasing the LTE interface rate per node leads to a higher network operation cost.

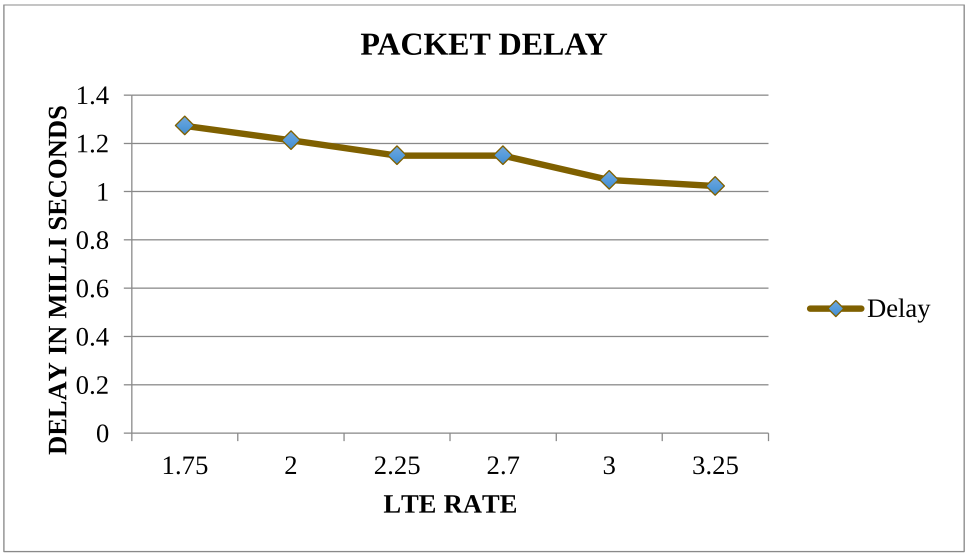

Figure 4.23: Packet delay with different LTE data rates

4.4.5.2 Packet Loss

When the LTE rate is increased from 1.75 to 2.25 Mbps (around 50% increase), the packet loss drops from 0.2% to 0.02% after which the packet loss is almost stabilized. Indeed, the significant decrease of packet loss is anticipated since more data rate is provided to the channel that does not suffer from packet collisions.

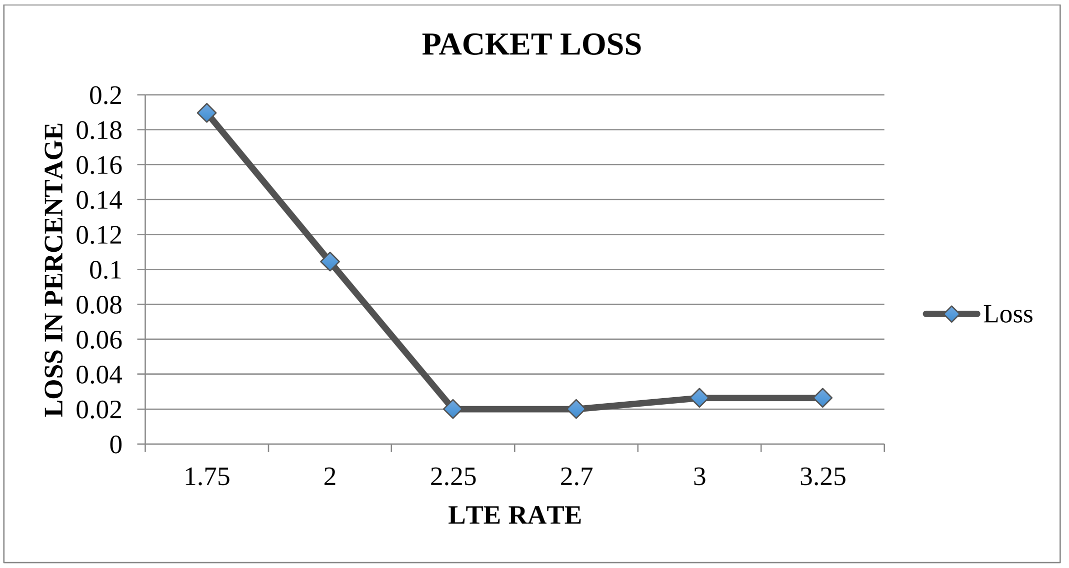

Figure 4.24: Packet loss with different LTE data rates

4.4.5.3 Energy Comparison in WiFi, LTE and Multi-homed Network

From figure 4.25, it can be observed that the energy consumed in WiFi remains almost the same with changing the LTE channel rate. This is expected, as the share of data traffic for the WiFi interface is not changed. . However, the energy consumed by the LTE interface decreases gradually as the rate is increased. This is due to shorter data transmission time. Apparently, increasing the LTE interface rate leads to better energy consumption but this comes at a higher operation cost.

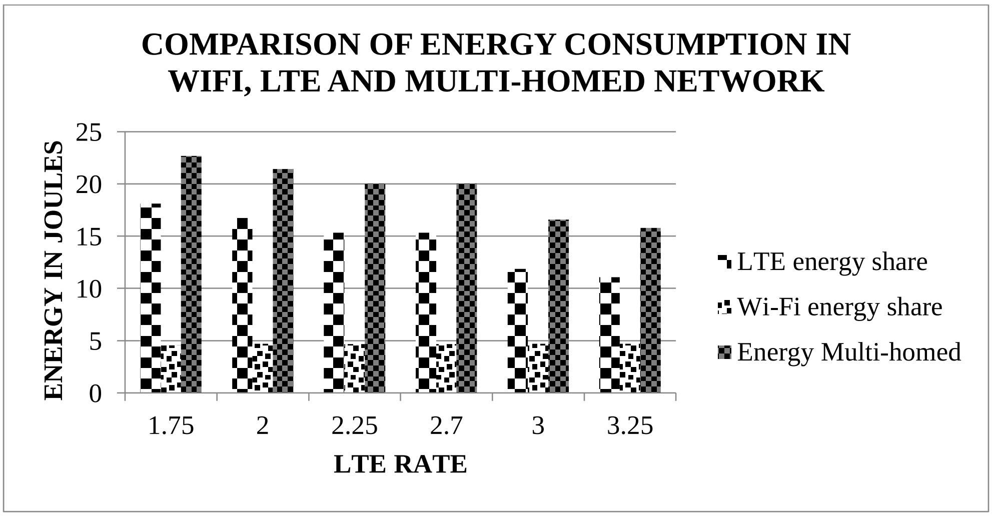

Figure 4.25: Energy consumption in LTE and WiFi interfaces with the LTE interface data rate

4.4.5.4 Energy Comparison in WiFi and LTE with Same Rate

This can be taken as a special case study from figure 4.25. When the LTE rate per node is 2.7 Mbps for a total of 20 nodes the rate is 54 Mbps. The WiFi rate is also fixed at 54 Mbps. It is very clear from the figure 4.16 that the energy consumed in LTE is much higher than in WiFi. Similar results were observed in many case studies in the past as in [43].

4.4.6 The Effect of WiFi Data Rate

In this section, the number of nodes is fixed at 20 and the low priority nodes represent 40% of the total number of nodes. The source rate is fixed at 250Kbps and the low priority source rate at 20 Kbps. The WiFi data rate is varied from 36 to 130 Mbps considering the IEEE 802.11n standard [44].

4.4.6.1 Packet Delay

As the source rate is fixed, increasing the WiFi channel rate leads to a performance enhancement in terms of packet delay. As can be observed from the figure 4.26, the delay is decreasing smoothly with increasing the WiFi channel rate. The delay is decreased from 1.06ms to 0.96ms when the WiFi rate is increased from 36 to 130 Mbps. The slight increase due to the fact that a significant part of the packet delay is attributed to the LTE interface.

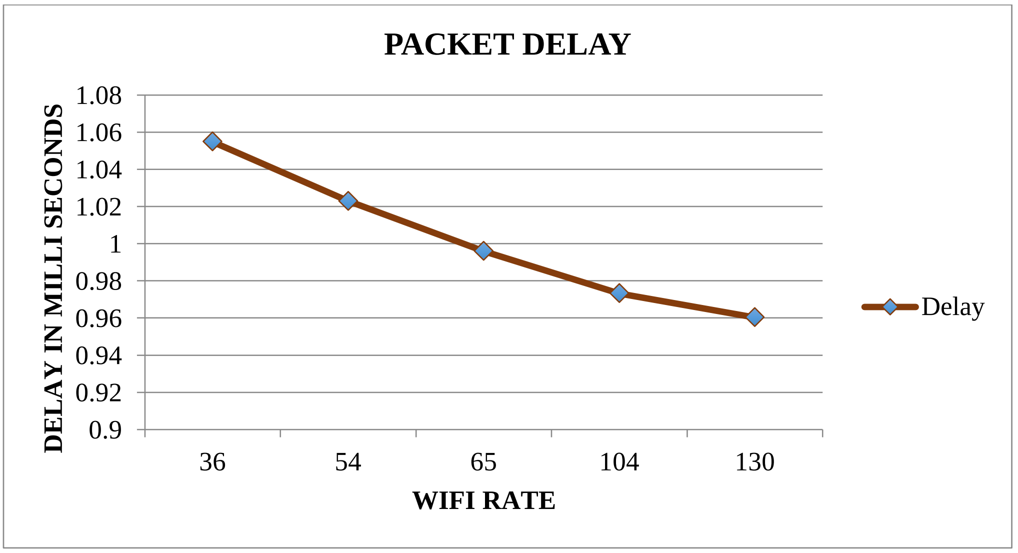

Figure 4.26: Packet delay with different WiFi channel rates

4.4.6.2 Packet Loss

As the WiFi channel rate is increased from 36 to 54 Mbps (almost 50% increase), the packet loss dropped from 0.1% to 0.02%. After that, increasing the data rate beyond 54 Mbps leads to a slight decrease in the packet loss. This is anticipated as a higher WiFi channel rate leads to a faster data transmission, and hence less packet collisions given certain source rate.

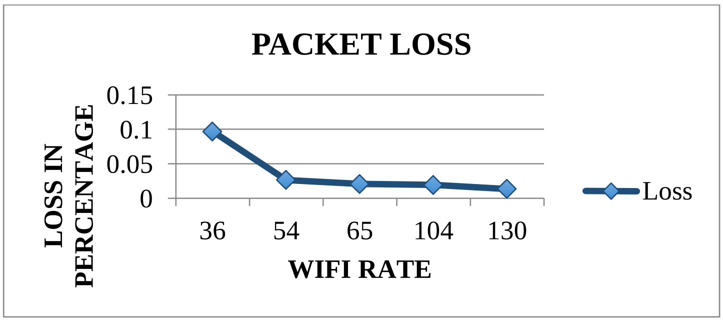

Figure 4.27: Packet loss with different WiFi data rates

4.4.6.3 Energy Comparison in WiFi and LTE

Here, we have fixed the LTE rate at 3.25Mbps and all other parameters like number of nodes at 20, source rate at 250 Kbps, low priority source rate at 20 Kbps except the WiFi rate. Therefore, the LTE energy consumption is expected to be almost constant. This is demonstrated in figure 4.28. However, the energy consumed in the WiFi interface is decreasing gradually as the rate is increased. This is due to shorter transmission and reception times for higher WiFi data rate.

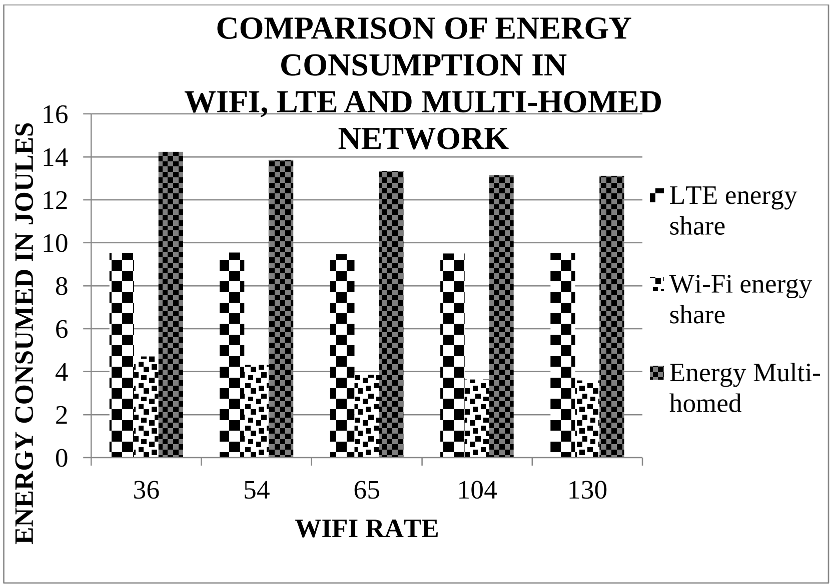

Figure 4.28: Energy consumption of LTE and WiFi interfaces with different WiFi channel rates

4.4.7 The Impact of Different Propagation Models

In this study, all the simulation is performed for different propagation models. The WiFi rate is 54 Mbps; LTE rate is 1.75 Mbps, the source rate at 250 kbps, and the low priority source rate at 20 Kbps. The low priority nodes constitute 40% of the total nodes. Three propagation models are considered. Two ray-Ground propagation model, Shadowing, and Free space. Free space assumes there is only one path of transmission and it is the line of sight path. Two-ray ground considers the line of sight along with a reflected path. Shadowing model considers the fading effects also in the path.

4.4.7.1 Packet Delay

The free space model represents an ideal propagation assuming that there is a clear line of sight between the transmitter and receiver. As in can be observed from figure 4.29, the packet delay remains the same for different propagation models, whereas in higher number of nodes, the free space shows less packet delay than the other models. The shadowing model leads to a slightly higher packet delay than the other models. This is because in shadowing propagation model, the shadowing effect is considered. Therefore, when the signal below a threshold power is received, it leads to improper operation of the MAC protocol. As observed in the figure below, free space shows a very small delay because it assumes an ideal transmission between sender and receiver [36].

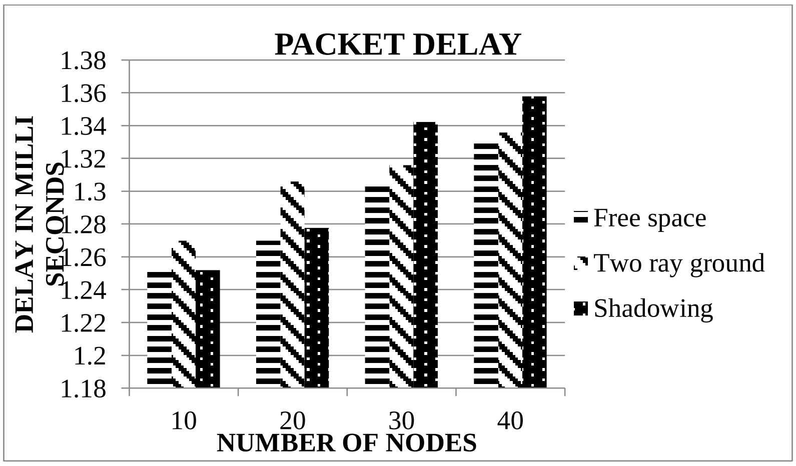

Figure 4.29: Packet delay in different propagation models

4.4.7.2 Packet Loss

The packet loss is almost negligible in the three models with less number of nodes. When the numbers of nodes approaches the network capacity, packet loss increases in all the models. Comparatively, the Free Space model has the lowest value of packet loss compared with the other models. Two ray Ground and Shadowing models lead to higher values of losses in all set of nodes. Generally, the study in this section reveals that the propagation model does not heavily affect the proposed network structure.

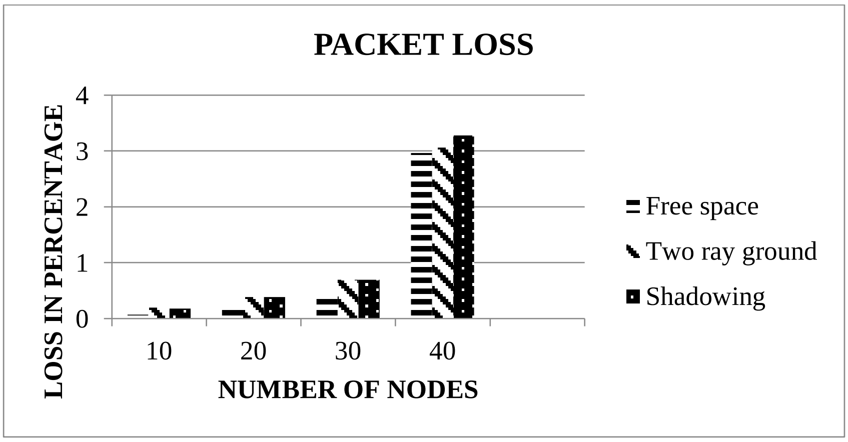

Figure 4.30: Packet loss in different propagation model

Chapter 5: Conclusion and Future Work

This study is an effort towards effective communications in smart cities. A city can be described as ‘smart’ in terms of communication when a highly efficient and sustainable network connects all the businesses, institutions, services, and especially citizens in the city. When adopting a smart network, we should consider the robustness, scalability, security, privacy, and energy consumption. In a smart city, various applications are involved, such as smart parking, analysing traffic congestion, and monitoring pollution levels. The design of an energy-efficient wireless network structure that can achieve an acceptable QoS level is currently under intensive research. We proposed a network structure that can support different types of smart-city sensors and applications. We focus on real-time video-surveillance applications, health-monitoring wearable devices, motion detectors, etc. Certain applications, such as video surveillance, demand a large bandwidth in order to properly operate. Others, such as temperature and pollution monitoring are delay-tolerant applications, which means they are less bandwidth-hungry but they may need large number of sensors to be deployed.

In the proposed network, the smart-city wireless sensors are equipped with two wireless interfaces. One is connected to a WiFi network, which is currently provided publically in some cities for facilitating Internet access in addition to smart-city applications. The other is connected to a cellular (LTE) network. The proposed multi-homed network is comprehensively studied using computer simulations. Two categories of applications are simulated, namely, high-priority (e.g., real-time) and low-priority (e.g., throughput-sensitive or non-real time). Different channel rates are considered for both LTE and WiFi interfaces. Also, different propagation models are investigated. In order to examine the capability of the proposed network, we consider a large density of sensor nodes (up to 40 nodes in a small area of 100 × 100 m^2), which are covered by a WiFi access point and an LTE eNodeB.

In the simulations, when the number of nodes increases, the packet delay, packet loss, and the per-node power consumption increase as anticipated (similar behaviour to single-interface networks). However, the impact on the satisfactory level of QoS is minimal in the proposed network structure. Regarding the penetration of low-priority nodes, various simulations are performed. The packet delay, packet loss, and energy consumption are generally high in scenarios where a large number of nodes are high-priority. In the proposed network structure, the packet delay and loss are generally negligible when most of the nodes are low-priority. Simulation experiments are conducted to study the effect of changing the data rate for LTE and WiFi interfaces for high- and low-priority nodes. The study shows that the multi homing network structure offers sufficient bandwidth (to satisfy the QoS required by various applications) even for low data rates of LTE and WiFi interfaces. This implies that our proposed network structure reduces the impact of the smart city sensors' applications traffic on the public WiFi and LTE networks without comprising the QoS level offered to these applications.

A case study is examined where the WiFi network data rate is equal to the total LTE eNodeB uplink rate available for the whole the cell. At the same data rate, the power consumption for WiFi interface is far lower than that for LTE interface. Regardless of the different energy-saving characteristics, the LTE interface consumes more than 20% of the energy consumed by the Wi-Fi interface. The performances of multi homing networks in different propagation models are studied.

Free Space, Two-ray Ground, and Shadowing are the models considered in our investigation. The performance of the proposed network under these three models is examined with regard to the packet delay, packet loss, and power consumption. In accordance with many previous studies for single-interface networks, the Free Space model exhibits a relatively smaller packet delay and packet loss [45].

Compared with the WiFi and LTE networks, the multi homing network yielded a better overall performance. The three networks were analysed with regard to the effects of the number of nodes and the source rate. The multi homing network exhibited a better performance with regard to the energy consumption.

Moreover, a comparison is conducted between supporting smart-city sensors by only a WiFi network, or by only an LTE network, or by the proposed multi homing structure. The results reveal that the proposed network structure reduces the overall transmit power, while generally providing better packet loss and packet delay than the other two single-interface network structures (WiFi or LTE). Furthermore, these sensors can achieve eco-friendly communication, which is very desirable given that the sensors are intended to have a long lifetime.

In the future, we plan to investigate other radio technologies that are supposed to support the fifth generation of cellular networks and examine their impact on smart-city applications and the QoS. We can extend the proposed architecture to accommodate these new technologies and study the impact and improvements.

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