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PERFORMANCE STUDY FOR CAPILLARY MACHINE-TO-MACHINE NETWORKS

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This thesis is submitted in partial fulfillment 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, Maisaa Othman Albaghdadi, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled *"Performance Study for Capillary Machine-to-Machine 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 Amin 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 Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions.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

Communication technologies witness a wide and rapid pervasiveness of wireless machine-to-machine (M2M) communications. It is emerging to apply data transfer among devices without human intervention. Capillary M2M networks represent a candidate for providing the reliable M2M connectivity. In this thesis, we propose a wireless network architecture aims at supporting a wide range of M2M applications (either real-time or non-real time) with acceptable QoS level. The architecture uses capillary gateways to reduce the number of devices communicating directly with a cellular network such as LTE. Moreover, the proposed architecture reduces the traffic load on the cellular network by providing the capillary gateways with dual wireless interfaces. One interface is connected to the cellular network, whereas the other is proposed to communicate to the intended destination via a WiFi-based mesh backbone for cost effectiveness. We study the performance of our proposed architecture by the aide of the ns-2 simulator. An M2M capillary network is simulated in different scenarios by varying multiple factors that affect the system performance. The simulation results measure average packet delay and packet loss to evaluate the quality-of-service (QoS) of the proposed architecture. Our results reveal that the proposed architecture can satisfy the required level of QoS with low traffic load on the cellular network. It also outperforms a cellular-based capillary M2M network and WiFi-based capillary M2M network. This implies a low-cost of operation for the service provider while meeting a high-bandwidth service level agreement. In addition, we investigate how the proposed architecture behaves with different factors like the number of capillary gateways, different application traffic rate, the number of backbone routers with different routing protocols, number of destination servers, and the data rates provided by the LTE and Wi-Fi technologies. Furthermore, the simulation results show that the proposed architecture continues to be reliable in terms of packet delay and packet loss even under large number of nodes and high application traffic rates.

Keywords: M2M, IoT, LTE, WiFi, capillary network, QoS, multihoming, heterogeneity, backbone, mesh network.

Title and Abstract (in Arabic)

دراسة الأداء لشبكات آلة إلى آلة العصبونية

الملخص

تشهد تكنولوجيا الاتصالات انتشار سريع وواسع للاتصالات اللاسلكية من نوع آلة لآلة. وهي تقنية متقدمة تسمح بتبادل المعلومات بين الاجهزة دون الاشراف البشري. الشبكات العصبونية تعتبر ذات كفاءة لضمان التوصيل في هذا النوع من الشبكات. هذه الرسالة تدرس بنيان شبكي يهدف لدعم مجال واسع من تطبيقات آلة إلى آلة مع جودة خدمة مقبولة، وذلك باستخدام شبكات عصبونية مزودة ببوابات لتقليل عدد الأجهزة الموصلة مباشرة مع الشبكات الخلوية مثل شبكات الجيل الرابع.و أيضاً تساهم البنية المذكورة في تقليل حمل التوصيل على شبكات الخليوي عن طريق تزويد البوابات العصبونية بواجهات تواصل ثنائية، أحدها لنقل البيانات باستخدام الشبكة الخليوية والآخر باستخدام شبكة الواي فاي. الأخيرة تتواصل مع الوجهة عن طريق شبكة من الموجهات لتحقيق كفاءة في الكلفة. دراسة الأداء تمت باستخدام برامج المحاكاة الحاسوبية المتقدمة من نوع ns-2 . تمت محاكاة عدة سيناريوهات فيما يخص البوابات العصبونية و في كل سيناريو تم تغيير قيم العوامل المختلفة التي تؤثر على قيمة جودة الخدمة. تم تقييم معيار جودة الخدمة عن طريق قياس التأخير أو الضياع في وحدات البيانات. نتائج المحاكاة أظهرت أن البنية المذكورة توصل لجودة خدمة مرضية مع حمل خفيف على شبكات الخليوي. و سبقت بالأداء شبكات آلة لآلة العصبونية التي تستخدم الخليوي او الواي فاي كلاً على حدى.المحاكاة شملت أيضا سيناريوهات يتغير فيها عوامل عدة منها عدد البوابات العصونية المستخدمة، معدل البيانات المرسلة، عدد الموجهات، وبروتوكولات التوجيه المتبعة، و كذلك عدد المخدمات في الوجهة و معدلات الإرسال المقدمة من مزود الخدمة الخليوي والواي فاي.

مفاهيم البحث الرئيسية: واي فاي، خليوية، عصبونية، جودة الخدمة.

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It is a pleasure to thank my friend Besintha, for the wonderful times we shared. She was a best friend, and a source of great emotional support.

Finally, my deep and sincere gratitude to my family for their continuous and unparalleled love, help and support. I am grateful to my husband for always being there for me. I am forever indebted to my parents for giving me the opportunities and experiences that have made me who I am. They selflessly encouraged me to explore new directions in life and seek my own destiny. This journey would not have been possible if not for them, and I dedicate this milestone to them.

Dedication

To my beloved parents and family

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List of Abbreviations

3GPP	Third Generation Partnership Project
4G	Fourth Generation
ACK	Acknowledgement
ANDSF	Access Network Discovery and Selection Function
AODV	Ad-hoc On-demand Distance Vector
BAN	Body Brea Network
BKRT	Backbone Routing Network
BLE	Bluetooth Low Energy
CN	Core Network
CR	Cognitive Radio
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CTS	Clear-to- Send
DIFS	Distributed coordination function Inter-Frame Space
DPS	Data Processing Station
DSR	Dynamic Source Routing
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
eNB	Evolved NodeB
EPC	Evolved Packet Core
ETSIs	European Telecommunication Standards Institute
H2H	Human-to-Human
IBM	International Business Machines

IEEE	The Institute of Electrical and Electronics Engineers Standards Association
IFS	Inter-Frame Space
IMT	International Mobile Telecommunications
IoT	Internet of Things
IPv6	Internet Protocol Version6
LAN	Local Area Network
LoWPAN	Low-power Wireless Personal Area Networks
LTE	Long Term Evolution
LTE-A	Long Term Evolution-Advanced
M2M	Machine-to-Machine Communication
MAC	Media Access Control
MAN	Metropolitan Area Network
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Out Output
MNO	Mobile Network Operator
MPDU	MAC Protocol Data Unit
MTC	Machine Type Communication
NAV	Network Allocation Vector
NS-2	Network Simulator
OFDMA	Orthogonal Frequency Division Multiplexing
PC	Personal Computer
PC	Personal Computer
PDN	Packet Data Network
PHY	Physical Layer

PL	Path Loss
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RAN	Radio Access Network
RF	Radio Frequency
RFID	Radio Frequency Identification
RTS	Request-to-Send
SIFS	Short Inter-Frame Space
SLAs	Service Level Agreements
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
VOIP	Voice Over Internet Protocol
WiFi	Wireless Fidelity
WLAN	Wireless Local Area Network
WMSN	Wireless Multimedia Sensor Networking

Chapter 1: Introduction

Machine-to-machine (M2M) communication is technology emerging rapidly to provide ubiquitous connectivity among devices without human supervision. This technology utilizes the Machine Type Communication (MTC) to enable networked devices to exchange information and perform actions without the manual assistance of humans. Recent reports developed by both Cisco and Ericsson discuss the expected growth in the number of connected devices by 2020 due to the introduction of the M2M market [1]. The chart in Figure 1 illustrates the growth of different categories of devices included in in the futuristic M2M applications. It is expected that M2M communications will spread out to include billions of smart MTCs in the next three to five years [2]. These numbers are the driving motives for both academicians and industrial researchers to find solutions and ideas to improve the machine type communication.

In this chapter, a general introduction to the topics related to this thesis is presented. We start with top seven wireless technologies utilized to implement M2M networks, with a brief on each and the applications that best suit each one. M2M communications has the power to reinvent business. Transformative technologies, such as PCs, assembly lines and mobile devices, have dramatically altered the way we do business, and M2M will be one of those technologies.

Political, technological and economic factors are coming together to make M2M more attractive than ever before. As new infrastructure replaces old, companies and governments have the opportunity to alter their businesses by implementing a technology strategy that is not only more efficient, but enables new levels of service, efficiency and economy.

Two significant factors are leading the way to M2M adoption: First, the sensors, devices and components that enable M2M are getting smaller, cheaper and more power efficient; second, the networks required to collect and deliver the data generated by billions of devices are already installed, like the cellular and the internet infrastructure, the researches and studies are challenged to design M2M systems matching with those infrastructure.

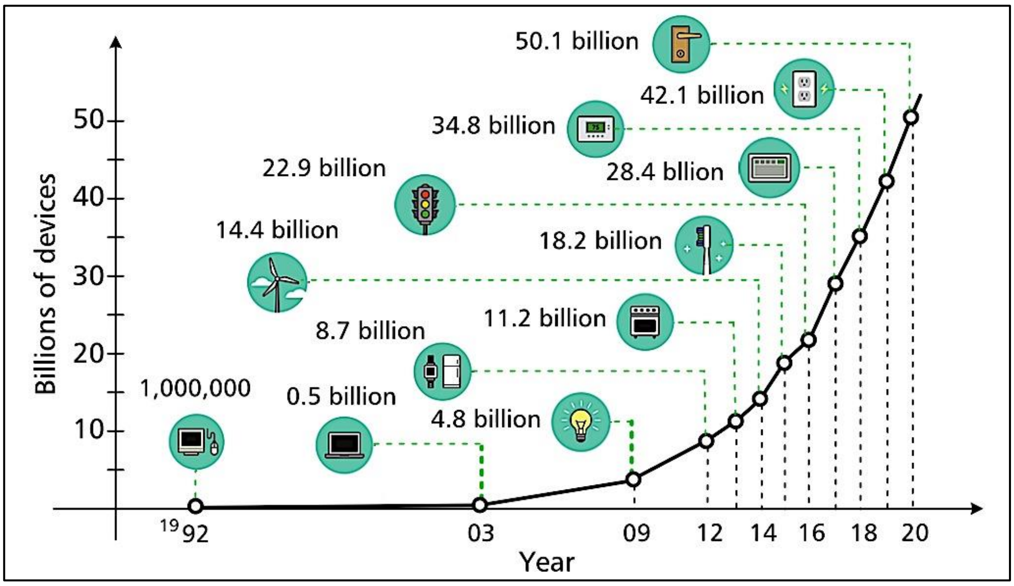


Figure 1: Expected number of connected devices to the Internet [3]

1.1 M2M applications

A machine_ to_ machine network enables end-to-end connectivity between MTC devices is comprised of radio network, access technology, gateway device, core network, and a data management server. The hardware, protocols, end-to-end delay reliability, and cost are factors influence the performance of an M2M network [4].

For instance, a device like water meter monitored by sensing node in “uplink”, and a device like valve programmed to actuate in “downlink”. Usually, the type of physical sensors and actuators used will directly affect the cost of M2M system.

The disintegration in current M2M markets definitely impacts large-scale M2M deployment, because most of the upright M2M solutions have been designed distinctly and independently from each other. However, when it comes to global coverage, cellular network standardizations, stability and reliability, together with the speed offered by recent cellular networks (LTE rates up to 150 Mbps uplink for mobile objects [5]), nominates wireless cellular technologies as the best candidate for the deployment of secured and trustworthy business critical M2M services [3]. This thesis discusses mainly M2M communication in LTE generation; the applications of M2M in 3GPP have been categorized, as in Figure 2, into different categories according the application field [6]. Each application is presented briefly in the following subsections with examples and some of the challenging requirements.

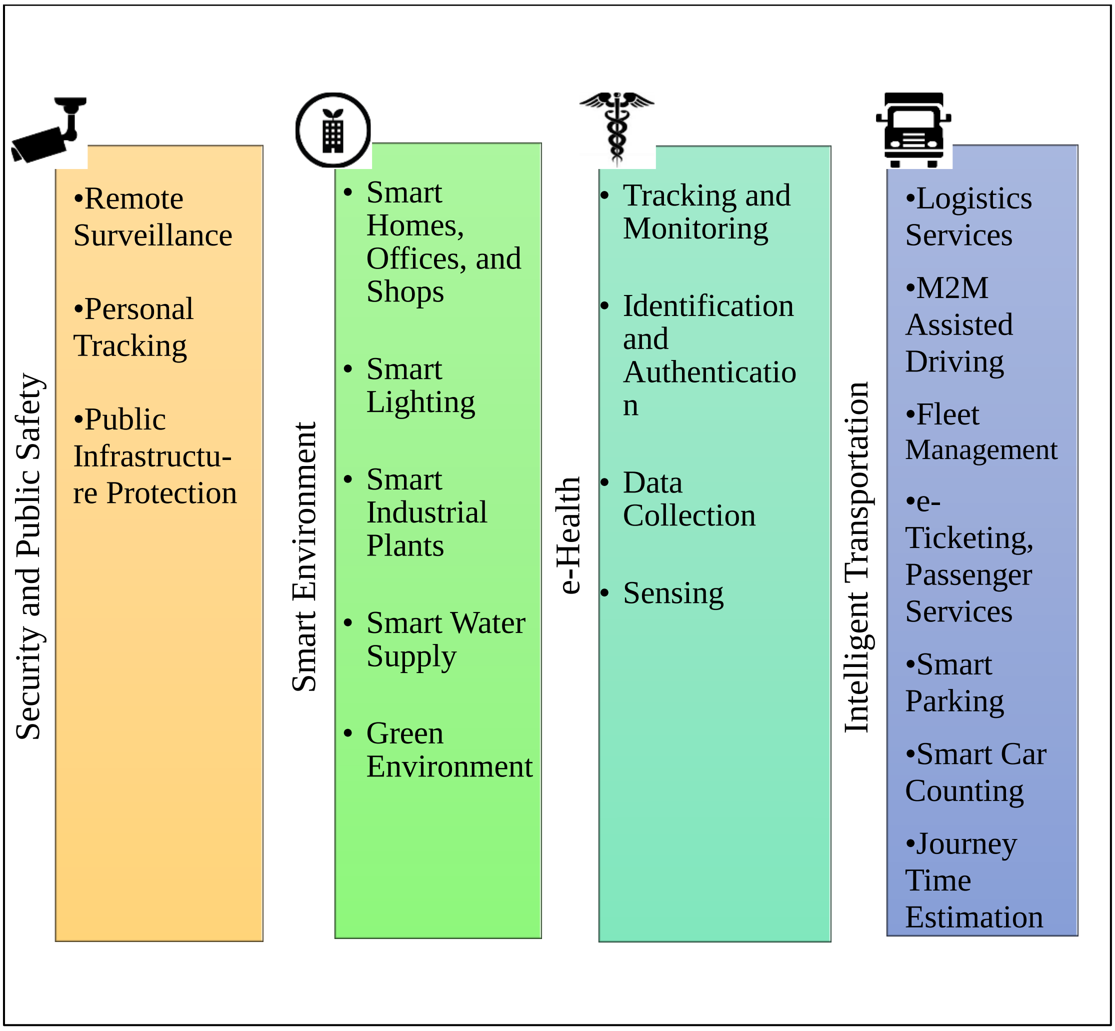


Figure 2 : M2M applications in 3GPP LTE [6]

1.1.1 E-Health

M2M communication can fulfill the following roles in healthcare applications [6].

1) Tracking and monitoring in various cases, such as tracking a patient or the function of an organ in a patient, inventory/stock to maintain reliable availability of materials, and remote medical treatments or operations.

2) Patient identification to reduce the risk of the incorrect treatment being given to patients, which usually occurs as a result of human error. Authentication is also

commonly used to grant privacy protection against possible medical data leakage and to ensure secure access to restricted areas and materials.

3) Data sensing and collection to reduce patient processing and treatment time by providing patients’ real-time biological indicators through the usage of sensor devices and by applying medical treatment automation through automatic data collection and transfer.

In order to enable successful e-health information acquisition by M2M applications, a typical body area network (BAN) of sensors has to be deployed around the patient’s body, allowing him/her to record the required biological parameters, such as blood pressure, body temperature, heart rate, weight, etc. [7].

M2M e-health sensors are expected to be strictly constrained by the factor of battery consumption, and therefore, it is preferable to forward the collected data using a short-range technology to a device that can act as an M2M aggregator or gateway [6]. Then, an access network, such as LTE, connects the M2M gateway to the core M2M network. Through the M2M core network, the M2M gateway is connected to the M2M server, which stores and possibly reacts to the collected data through the M2M application user, such as a healthcare remote monitoring center; see

Figure 3. In this scenario, the gateway could be a fixed device, such as a PC, or a mobile device, such as a cell phone or a standalone device carried on a user’s keychain or worn around his/her wrist or neck.

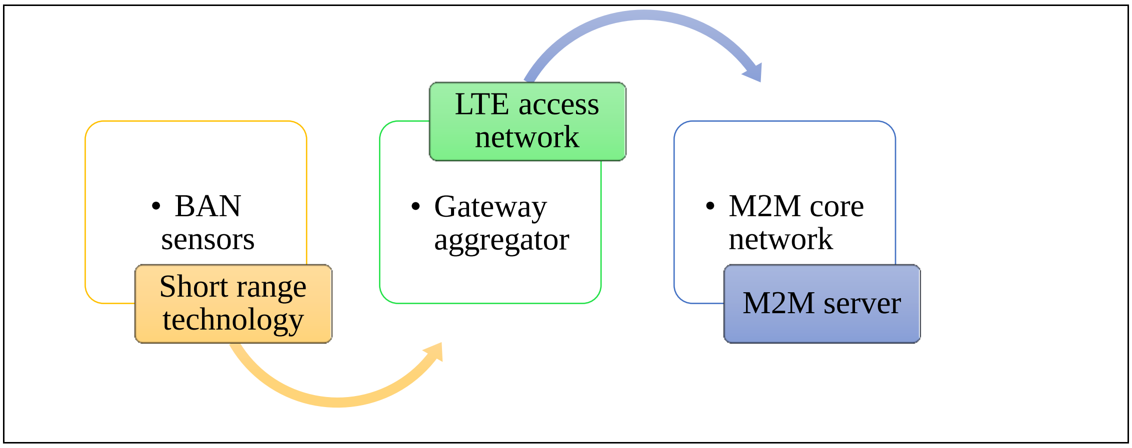


Figure 3: M2M scenario for e-health [6]

1.1.2 Smart Environment

Advances in wireless communications can improve the quality of human life significantly. According to this concept, people may be surrounded by M2M communication systems everywhere, at home and in offices, industrial plants, city streets, highways, etc.

M2M communication can provide solutions for monitoring electric power and water consumption to support a green environment. Some of the futuristic M2M applications in smart cities that are discussed fall into the following categories.

1) Homes, offices, and shops can be turned into smart environments [8] by installing M2M communication sensors and actuators. Various devices used every day lead to more efficient energy consumption, as well as a more comfortable lifestyle. For example, heating and cooling can be controlled to maintain a desirable room temperature, and lighting in rooms can be adapted to the time of day and the number of people inside the rooms; an improvement in energy saving can be achieved by switching off idle electrical appliances. Moreover, emergency situations, such as fire

or burglary, can be detected with appropriate M2M monitoring and alarm systems associated with the installed M2M devices.

3) Industrial M2M communication will enhance intelligence in control systems to improve the automation in industrial plants by means of several techniques [6], such as the collection and exchange of data among sensors, actuators, and RFID tags attached to the products. Even vibration in industrial machinery can be monitored and a warning can be signaled when appropriate. Moreover, the effects of a device fault in a production line can be predicted based on the information stored in the M2M controller server.

4) Currently, there is rapid growth in the demand for water worldwide and water consumption is rising at twice the rate of population growth [6]. M2M sensors [9] can discover water leakage instantaneously, apply precise control to water piping systems by measuring pipe flow data regularly, and broadcast alerts, transmitting an emergency message to the M2M controller server via the core network if water usage exceeds an estimated normal range. Finally, they can determine the locations of leaking pipes to avoid the waste of water resources.

1.1.3 Intelligent Transportation

Transportation services form an active market for M2M communication technology [10]. The following list presents some of the open-ended applications streaming in this field.

1) Logistics services, such as the identification of traffic routes, monitoring of transported goods, tracking of vehicle locations, and monitoring of temperature,

humidity, light, weight, and more parameters, can be achieved by means of M2M sensors and tags, as well as other services.

2) M2M systems can improve the productivity of a fleet company by facilitating fleet management through tracking vehicles and cargo containers to keep the data on locations, fuel consumption, temperature, and humidity updated, in order to increase fleet safety and reduce accident rates.

3) Mobile e-ticketing [6] can enhance the effectiveness of ticketing, reduce costs for transportation service providers, and increase the convenience of passengers. Figure 4 illustrates a probable e-ticketing process utilizing an enabled device that acts as an M2M sensor node.

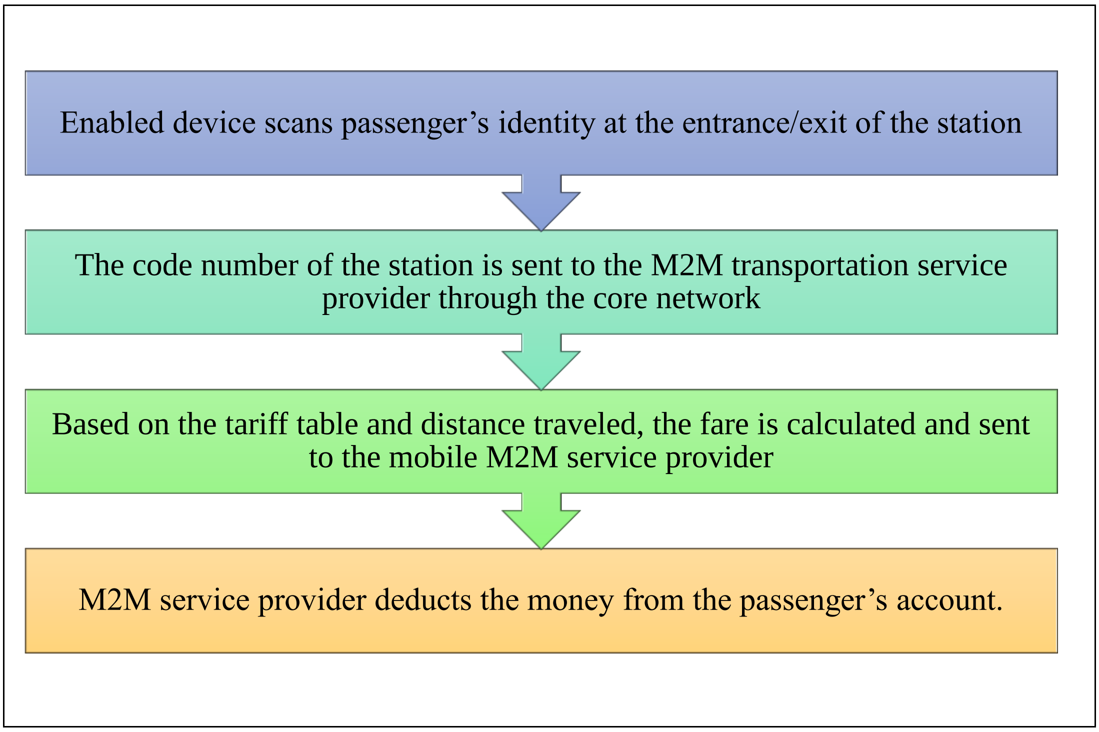


Figure 4: M2M e-ticketing process [6]

4) Smart car-counting supports transportation and traffic management, which poses significant challenges with the huge growth in urban populations. SenseField offers

an end-to-end solution for traffic management that collects data by means of which it eases traffic flow and facilitates smooth transportation in city regions [6].

Figure 5 shows the flow of the process.

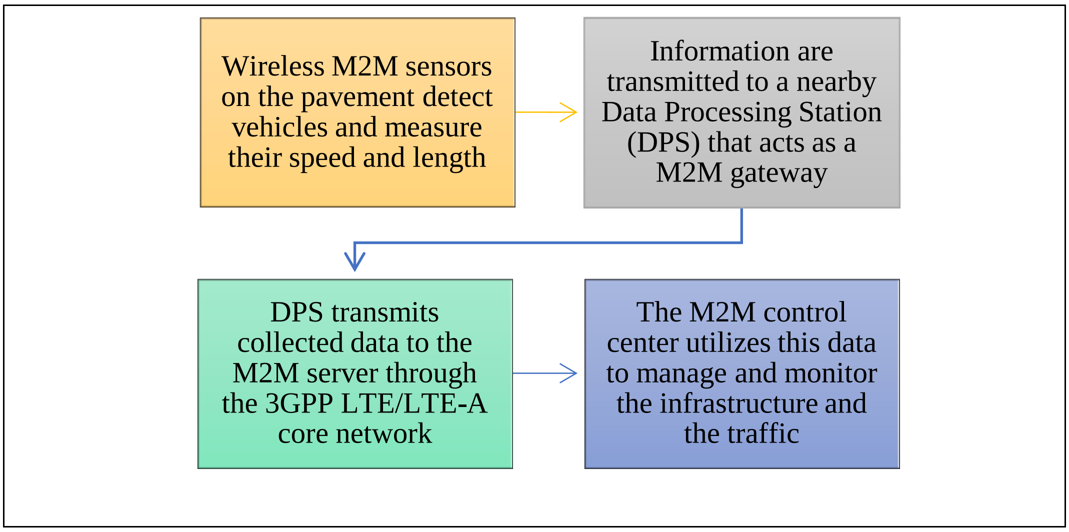


Figure 5: Traffic management solution process provided by Sensefield [6]

6) To estimate [6] a traveling time for a vehicle through a certain route in any time and conditions, there should be an adequate and efficient data collection system in real time. Bit carrier offers a solution for traffic information and management in any kind of road. A network of M2M sensors used for auditing the Bluetooth and WiFi public frequencies of mobile devices, a network of M2M servers used to host the databases, and an online web client displays all results regarding speed, travel times and incidents. The basic elements of that solution are shown in Figure 6.

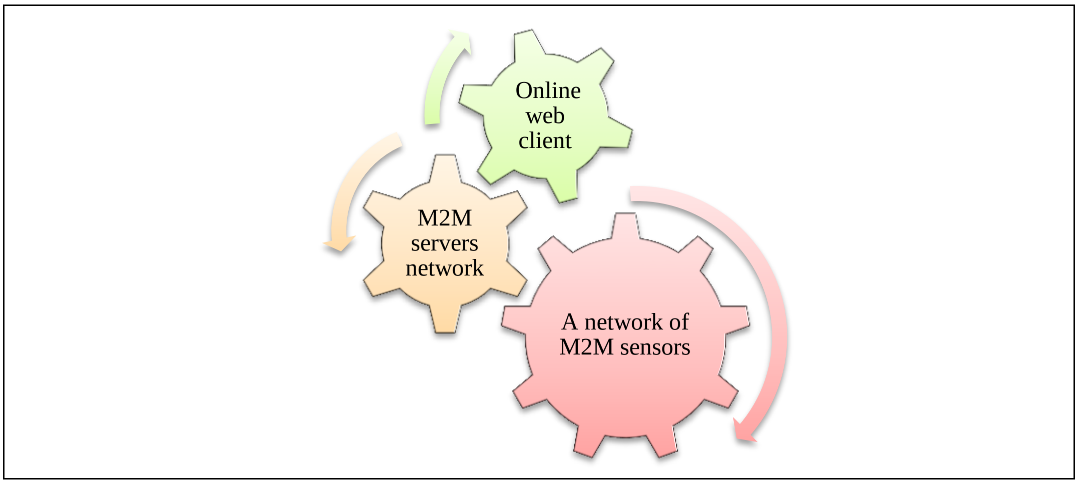


Figure 6: Elements of journey time estimation system provided by BitCarrier [6]

1.1.4 Security and Public Safety

Public safety monitoring and management can be automated and simplified using the M2M communication technology. Deployment for remote surveillance, remote alarms, and personal tracking will be rapid, flexible, and cost-efficient, as described in [6].

1) Remote surveillance can be used to monitor open areas, valuable assets, people, or even pets to provide appropriate protection. M2M sensors in video cameras are used to transmit signals either continuously or periodically to detect incidents and notify authorities. In particular, M2M applications can instantaneously notify the user if objects are transferred to/from a certain location (e.g., home or office), and provide the accurate location of the events.

2) Personal tracking provides information about the location of individuals on a real-time basis automatically or on demand. Persons, property, and/or animals have to be equipped with convenient and suitable M2M devices containing an M2M communication module and an optional GPS unit to send location information to an

M2M application server via a 3GPP LTE/LTE-A core network, which sends the information via the Internet to the M2M database server.

1.2 Capillary M2M Networks

An M2M capillary network consists of a number of devices (e.g., sensors) forming a cluster, with a head device known as a capillary gateway. The function of the gateway is to enable the monitoring and management of capillary clustered devices in order to reduce the overall signaling and control process [11]. The special requirements generated by the rapid emergence of cellular-based M2M applications necessitate a major reconstruction of future cellular networks. In order to accomplish a smooth transition, the European Telecommunications Standards Institute (ETSI) committee proposed an M2M architecture, where the gateway acts as a traffic aggregator and a protocol translator for the capillary network [12]. Recent research studies addressed several methods to enhance the capillary network performance. In [13], a robust capillary gateway designed to integrate capillary M2M networks with 3GPP effectively was presented. In [14], a method providing optimal gateway selection by the sensing node was proposed.

1.3 LTE/WiFi Multi-homing Technique

Internet traffic has been growing rapidly in recent years. The demand for video traffic is predicted to increase 11-fold by 2020 [15]. Although wireless technologies are becoming more advanced, the existing wireless structures may not be sufficiently capable of delivering the desired contents in high quality with this massive growth of traffic. As wirelesses user equipment (UE) usually provides multiple network interfaces (e.g., WiFi and cellular), researchers are anticipating the deployment of new wireless access techniques. The research activity on the integration of accesses has made simultaneous data exchange through several interfaces (known as aggregation or multi-homing) possible. A technical strategy that allows the coexistence of LTE and WiFi was proposed in 3GPP Release 13 [16]. In addition, a function was proposed to guide the user to select the LTE/WiFi network option under the policies defined by the operator. This function is an optional element in the evolved packet core (EPC) network and defined as an access network discovery and selection function (ANDSF) [17].

In this thesis, a capillary M2M heterogeneous network architecture is proposed. The proposed architecture employs a multi-homing technique and allows the simultaneous usage of the WiFi and the LTE interfaces in the capillary gateways, which supposed to be not a standard WSN node as it is provided by a dual interface. Using comprehensive computer simulations, the performance of the proposed network architecture was studied and compared with the case where only the LTE or the WiFi technology is used.

1.4 Quality of Service Metrics

As defined in [18], quality of service (QoS) constitutes a set of measurable service requirements for evaluating the level of service quality provided to the user. It is usually characterized by end-to-end packet delay, packet loss ratio, available bandwidth, and jitter [19]. In general, in wireless architectures, the typical issue related to QoS is bandwidth limitation [18].

The architecture proposed in this thesis uses capillary gateways to reduce the number of devices communicating directly with a cellular network, such as LTE. Moreover, the proposed architecture reduces the traffic load on the cellular network by providing the capillary gateways with dual wireless interfaces. In the proposed architecture, one interface is connected to the cellular network, whereas the other is proposed to communicate with the intended destination via a WiFi-based mesh backbone. We evaluated the performance of our proposed architecture by means of the ns-2 simulator.

The results of this study show that the proposed architecture can significantly improve the QoS level of M2M applications as compared with that of a typical cellular LTE- or WiFi-based M2M network. Moreover, the overall cost of using the architecture is lower for the achieved QoS level, which allows the service provider to establish profitable service-level agreements.

1.5 Thesis Organization

The thesis is organized as follows. Chapter II discusses M2M enablement in different communication networks, and presents the background of WiFi and LTE networks and standards. Chapter III describes our system model, including all the network components and topology. Chapter IV discusses the simulation model and the parameters used in the simulation, and presents an illustration and discussion of the results. Chapter V concludes this thesis.

Chapter 2: Background and Literature Review

The cellular infrastructure and standards are considered to provide a ready-to-use architecture for the implementation of M2M communications. However, transmission for M2M applications over cellular networks presents a major challenge because of the dissimilar data transactions, varied applications, and large number of connections [20].

It is expected that M2M communication usage will spread to include billions of smart devices in the next three to five years [21]. The existing cellular networks are capable of providing an infrastructure that is prepared for implementing M2M communications [6]. Moreover, 3GPP LTE/LTE-A cellular networks have been architecturally enhanced to enable M2M services. The main obstacles to handling large numbers of M2M terminals with the support of cellular networks were removed by the introduction of capillary M2M [21]. However, it is known that the reliability of capillary M2M systems remains poor and the packet delay is unbounded [22].

M2M systems should support the different frequencies of data delivery/reporting required by the M2M applications as listed below [9].

- Periodic reporting, where the time period is defined by the M2M application (e.g., daily or weekly reporting of smart water and electricity metering).

- Reporting based on a demand having two possible modes, one of which is instantaneous collection and reporting of data (e.g., current weather information) and the second the reporting of data that were pre-recorded at a specific time period.

- Event-based reporting (e.g., reporting of water leakage location information in a smart piping system).

Different wireless technologies have been used to implement M2M systems. In this chapter, we first present the most frequently used technologies.

2.1 Seven Leading M2M Wireless Technologies

Many professionals in the telecommunication industry are frequently asked to make recommendations about service providers, networks, and software solutions. The technology needed to implement an M2M communication system basically depends on two requirements [23]: coverage range and battery life. For example, WiFi cannot be considered when a long range is required and a battery life of more than a few days is essential; cellular networks also cannot be considered. In the last decades, seven technologies have mainly represented the leading providers: WiFi, Cellular, Bluetooth, Bluetooth Low Energy - BLE Bluetooth, 6LoWPAN, ZigBee, and Symphony Link. Table 1 shows the most common M2M applications and the most suitable wireless technology for each according to Link Labs [23].

In this thesis, a combination of WiFi and cellular technology to form a capillary network is proposed in order to enhance the performance of the M2M system. An overview of WiFi and cellular communication technology follows.

Table 1: Leading M2M wireless technologies

Wireless technology	M2M applications
WiFi	Home security systems Sensor-based lighting Smart home thermostats Smart streetlights

	Parking meters
Cellular	Asset tracking for transportation fleets Keyless locking systems
Bluetooth	Wireless headsets File transfers between devices Wireless keyboards and printers Wireless speakers
Bluetooth Low Energy **BLE**	Blood pressure monitors Activity and performance trackers (e.g. Fitbit) Industrial monitoring sensors Geography-based, targeted promotions (iBeacon) Public transportation apps
6LoWPAN	Smart metering Smart home (lighting, thermostats) Essentially
ZigBee	Wireless light switches Electrical meters Industrial equipment monitoring

In this research a combination of WiFi and cellular technology as a capillary network is proposed to enhance the performance of the M2M system. Following an overview of WiFi and cellular communication technology.

Our research is focused basically on cellular and WiFi networks, which are reviewed in detail, and we give a brief overview of other wireless technology used in the Internet of Things (IoT).

2.1.1 Bluetooth

The name Bluetooth is used for a wireless technology standard, not only for the audio device frequently used to allow hands-free communication. Clearly, the two are related, but the wireless connection between a phone and the earpiece is referred to as Bluetooth, not the hardware itself. Bluetooth was developed as a means of exchanging data over a short range without the need for a hardwired connection, making Bluetooth technology perfectly suited to wireless headsets, hands-free talking on a mobile phone while in a car, and wireless file transfer. Bluetooth operates in the 2400-2483.5 MHz range within the ISM 2.4 GHz frequency band. Data are split into packets and exchanged through one of 79 designated Bluetooth channels, each of which has 1 MHz of bandwidth.

2.1.2 Bluetooth Low Energy - BLE Bluetooth

Bluetooth low energy (BLE) entered the market in 2011 as Bluetooth 4.0 [24]. The key difference between BLE and Bluetooth is in BLE's low power characteristics. Although this may appear to be a negative attribute, it is in fact extremely positive in reference to M2M communication. When the power consumption is low, a small battery is sufficient to power applications for four or five years. Although this does not provide ideal conditions for mobile device conversations, it is vital for applications that need to exchange only small amounts of data periodically. Similarly to Bluetooth [24], BLE operates in the 2.4 GHz ISM band. However, unlike classic Bluetooth, BLE remains in sleep mode unless a connection is initiated. The actual connection times constitute only a few ms, whereas the duration of a Bluetooth communication is ~100 ms. The reason why BLE connections are short is the high data rates, which reach 1 Mbps. There are several additional features in the BLE specification, such as different data rates, ranges, and the possible number of nodes; however, lower power consumption is the main differentiating feature.

2.1.3 6LoWPAN

6LoWPAN comprises an updated version of the internet protocol (IPv6) with low-power wireless personal area networks (LoWPAN) [22]. As a result, 6LoWPAN allows wireless data transmission via Internet protocols, even for devices limited by low processing capabilities. This improvement expanded IoT applications to include small device applications, such as home-based sensor networks. LoWPAN is the most recent competitor of ZigBee to enter the market [23]. 6LoWPAN is capable of communicating with devices standardized by IEEE 802.15.4 through a bridge device, as well as with other types of device that use an IP network link, such as WiFi. 6LoWPAN is recommended for use as a wireless connection inside a home-based capillary cluster in which the sensors are equipped with a short-range interface [25].

2.1.4 ZigBee

ZigBee is short-range wireless mesh networking standard, the power and cost of which are known to be low. Data items in a ZigBee network continue hopping around a mesh of transceivers until they find a route to the Internet, exactly like honeybees performing their zigzagging dance to find their way back to the hive, where they deposit their honey. This is the origin of the name ZigBee. Zigbee is most commonly deployed for personal or home-area networks or in-between devices that form a wireless mesh network connected to networks activated over longer ranges [26]. ZigBee is standardized with IEEE 802.15.4, but unlike 6LoWPAN, it does not use IP protocols to communicate with other types of device [23]. The advantage of

ZigBee [27] is that the mesh nodes remain in sleep mode most of the time, which extends battery life significantly.

2.2 WiFi Standards and Features

WiFi [28] is a wireless technology operating in the unlicensed spectrum; anyone can deploy it anywhere. It requires cheap and simple hardware, and thus, is the most widely used wireless network worldwide. The Wireless-Fidelity Alliance is a trade association established to endorse wireless local area network (LAN) technologies and to allow operable testing, as well as international standards. The term WiFi is the well-known trademark of the association. Officially, any device that carries the WiFi name and logo has to be presented to and licensed by the WiFi Alliance. However, in practice, the term WiFi refers to any networking product constructed according to IEEE 802.11 standards.

The first IEEE 802.11 protocol was outlined in 1997 as a direct adjustment of the Ethernet standard (IEEE 802.3) to the field of wireless communication, although it was not announced until 1999. The standard features allowed anyone to easily install a wireless extension for his/her LAN setup. These features comprise simplicity, convenience, easy placement, and operation in the unlicensed 2.4 GHz ISM band. Currently, most new PCs, laptops, tablets, and smartphones are WiFi-enabled. The performance of WiFi can be summarized as follows.

- WiFi affords no bandwidth or latency guarantees or delegation to its users.
- The bandwidth provided is usually variable based on the signal-to-noise ratio (SNR) in its environment.
- The transmission power is limited to 200 mW, and may be lower in some

regions.

- The amount of spectrum is restricted to 2.4 GHz and the most recent 5 GHz bands.
- The design of WiFi access points is such that their channel assignments overlap.
- WiFi peers and access points strive to access a consistent radio channel.

It can be stated that WiFi's lack in terms of range is compensated by its speed and bandwidth. WiFi can be used for local-environment IoT applications or in a distributed manner, if "Wide Area WiFi" has been installed in the area [23]. Barcelona is a model example of a smart city with citywide WiFi access, which allows its citizens to implement M2M applications easily.

2.3 IEEE 802.11 Standard

The IEEE 802.11 standard is a set of physical layer (PHY) and media access control (MAC) characterizations. It is specifically for implementing computer communication in the 900 MHz and 2.4, 3.6, 5, and 60 GHz frequency bands over wireless LANS (WLANs). This standard was created and released by the Institute of Electrical and Electronics Engineers (IEEE) LAN/MAN standards committee (IEEE 802). An initial main version of this standard was released in 1997 and has undergone successive improvements and amendments. The standard and its amendments form the basis for WiFi network products. Figure 7 illustrates the standard layering.

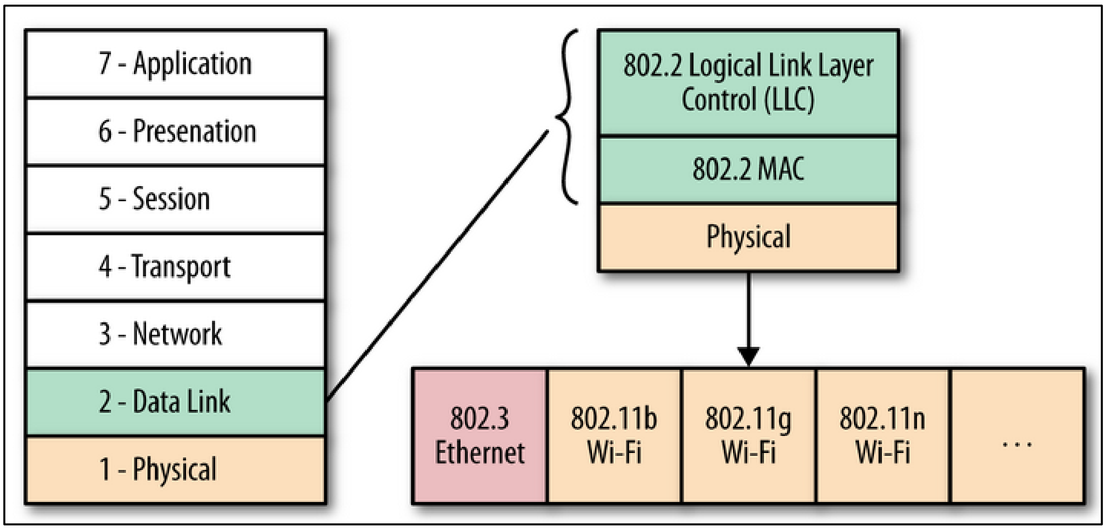


Figure 7: IEEE 802.11 standard layering [29]

Version 802.11b of the standard allowed the daily use of WiFi; nevertheless, the IEEE 802 Standards Committee continued to release updated protocols with increased throughput, newer modulation methods, multi-streaming, and several other innovative features.

How does IEEE 11.802 operate [29], [30]? IEEE 802.11 is based on carrier sense multiple access/collision avoidance (CSMA/CA). The time is divided into time periods corresponding to a time unit known as a time slot. The back-off time is a random integer number equal to a number of time slots. Initially, the back-off time is in the range 0-31 time slots, and it is computed by the station.

A ready-to-send station waits for completion of other transmissions. Every station must wait for a time period called an inter-frame space (IFS). When a station needs to send data, it starts sensing the shared medium. If the medium is idle for the duration of an IFS, the station may start sending, whereas if the medium is occupied the station must wait for another available IFS. The station then has to wait for additional back-off time, which is randomly generated. Throughout the back-off time, the station continues sensing the medium at each time slot. If another station utilizes the medium during the back-off time of the station, the timer stops the back-off timing and resumes only when the channel is again idle. A high-priority frame waits a short IFS (SIFS).

Figure 8 shows the time slots diagram.

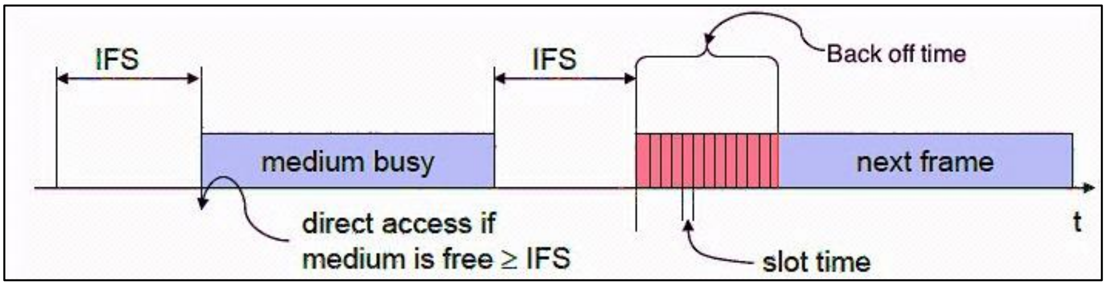


Figure 8: CSMA with collision avoidance [29]

When the back-off time expires, the station starts transmitting a frame. The back-off time interval must be doubled if a collision occurs. After a certain number of successive collisions, the frame is dropped. An acknowledgment frame is used to indicate a successful transmission. When a station receives a frame without error, it replies with an acknowledgement (ACK). The sending station interprets the non-arrival of an ACK as a frame loss, waits for a back-off interval, and then retransmits. Frame duplication is identified by the sequence packet numbering used by the receiving station.

Request-to-send (RTS) and clear-to-send (CTS) constitute a mechanism used to decrease the number of collisions and save more bandwidth in the carrier in the IEEE 802.11 layer. RTS and CTS are control frames (to be distinguished from data frames) used by a station to engage the channel bandwidth before sending an MAC protocol data unit (MPDU). A source station first transmits an RTS control frame, including the time duration field. All the stations in the same area read the duration field and set network allocation vectors (NAVs) accordingly. After the idle IFS period elapses, the destination station replies to the RTS packet with a CTS packet. Other stations can hear the CTS packet read the duration field and accordingly update their NAVs. If the CTS packet is successfully received, then the source station is almost guaranteed that the medium is steady and ready for successful MPDU transmission. By using this technique, stations are able to update their NAVs upon the information carried in RTS and CTS packets, which effectively avoids the problems that arise because of the existence of a hidden station.

2.4 Overview of Cellular Networks

A cellular mobile system is a communications system that uses a cell-based structure, as shown in Figure 9. A cell is the main topographical service region of the cellular wireless communications system. The system depends on a huge number of low-powered wireless transmitters to provide signal coverage in the cell. The demand on the service varies with the density of subscribers in a particular area, which affects the cell size and the power level of the transmitters. A mobile communication provider must ensure a faultless service, even when a mobile user passes from cell to cell. The service is maintained by using a “hand off” technique between the cells involved. A main feature of cellular systems is the reuse of frequencies: the same channels utilized in one cell can be reused in other cells located at a distance. An additional feature is the flexibility to accommodate growth in the number of subscribers, which is achieved by means of creating additional new cells in the uncovered area, or even overlapping cells in the existing coverage areas. Cellular communication networks are known as wide area networks; they are capable of providing signal coverage in a km order range. They are also classified as location-independent, since a subscriber is served with a connection regardless of his/her location. Moreover, mobile systems always guarantee high capacity through frequency reuse and clustered cells.The number of subscribers that can communicate simultaneously in a certain area is given by

$$N = \frac{m\,W}{C\,B} \tag{1}$$

where m is the number of cells covering an area, C is the spatial reuse factor (number of cells per cluster), B is the bandwidth required by a user, and W is the total bandwidth available. The signal to interference ratio (SIR) value at user i can be calculated by

$$N = \frac{Prxij}{\sum_{j=1}^{k} Prxij} \tag{2}$$

where Prxii is the received power at user i from base station i, Prxij is the received power at user i from base station j (which has a co-channel with base station i), and k is the number of co-channel cells.

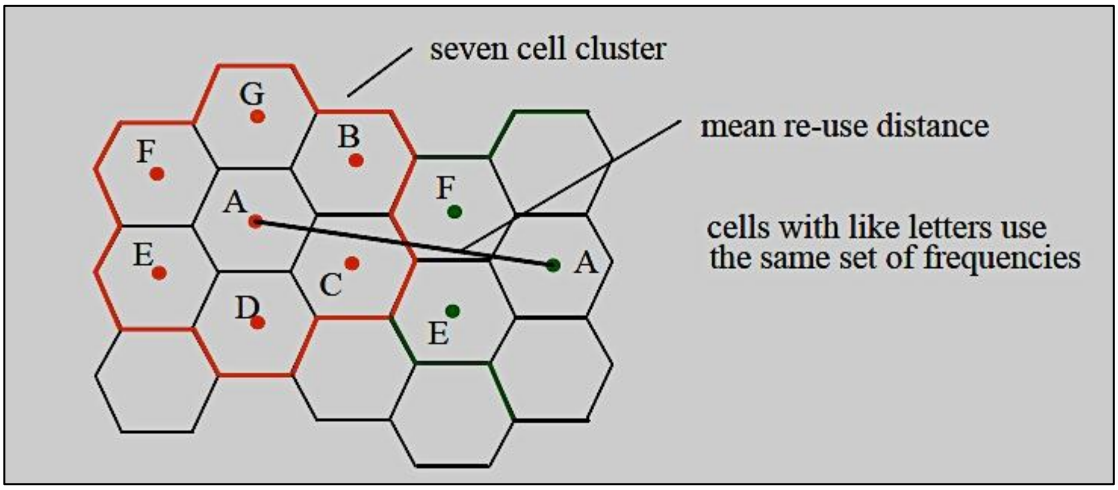


Figure 9: Cellular network topology [31]

2.5 M2M Communication over Cellular Networks

Critical business M2M applications require secure and reliable networks to allow their successful implementation. Cellular network maturity, stability, competent standards, and worldwide coverage, together with the increasing speed offered (up to 150 Mbps LTE rates for mobile UEs), mean that cellular technologies have been nominated as the best candidate for M2M advanced service deployment [3]. In addition, cellular networks are preferred to Ethernet and WiFi networks, which provide only local coverage.

Users are already familiar with the established cellular infrastructure, and therefore, the interest in M2M is attracting mobile network operators (MNOs) to become active players. Research studies in the M2M field have focused on standardization, practical models, business solutions, and facilities. The implementation of only a few M2M applications over global system for mobile communication (GSM) networks has been attempted. For instance, the GSM World Congress deployed a smart coke vending machine in the year 2000. The machine was capable of sending a periodic SMS over a GSM network to notify the supplier of the amount of coke available. Starting in 2002, fourth generation communication (4G) was approved by International Telecommunication Unit Radio (ITU-R) as an advanced global mobile telecommunication; it is mainly an IP packet switched network (based on IPv6), the PHY layer of which is based on orthogonal frequency division multiple access (OFDMA) and uses multiple-input multiple-output (MIMO) technology. The LTE data rate is up to 1 Gbps for low mobility and 100 Mbps for high mobility, and low packet delay is a basic feature [32]. The wireless communications standard 4G LTE was developed by the 3GPP, which is a collaborative association between telecommunication groups. The aim was to reach a high data rate for mobile services, while also considering M2M communication [33]. This standard was initiated at the 3GPP conference held in Toronto in 2004 and was departed as LTE work in 2006.

2.5.1 MTC Features in Different LTE Releases

The first generation of a fully featured MTC over LTE devices emerged in 3GPP Release 12, which was published in March 2015. In this release, the 3GPP committee defined a new profile, referred to as category 0 or CAT-0, for low-cost MTC operation. In addition, global coverage enhancement was guaranteed for all LTE duplex approaches.

On the other hand, in the proposed 3GPP Release 13 for LTE-A, MTC applications constitute the main mass of the contribution. Its main goal is to further enhance the MTC LTE-based UE beyond that in 3GPP Release 12 [34].

Figure 10 highlights the LTE enhancements regarding MTC in each release.

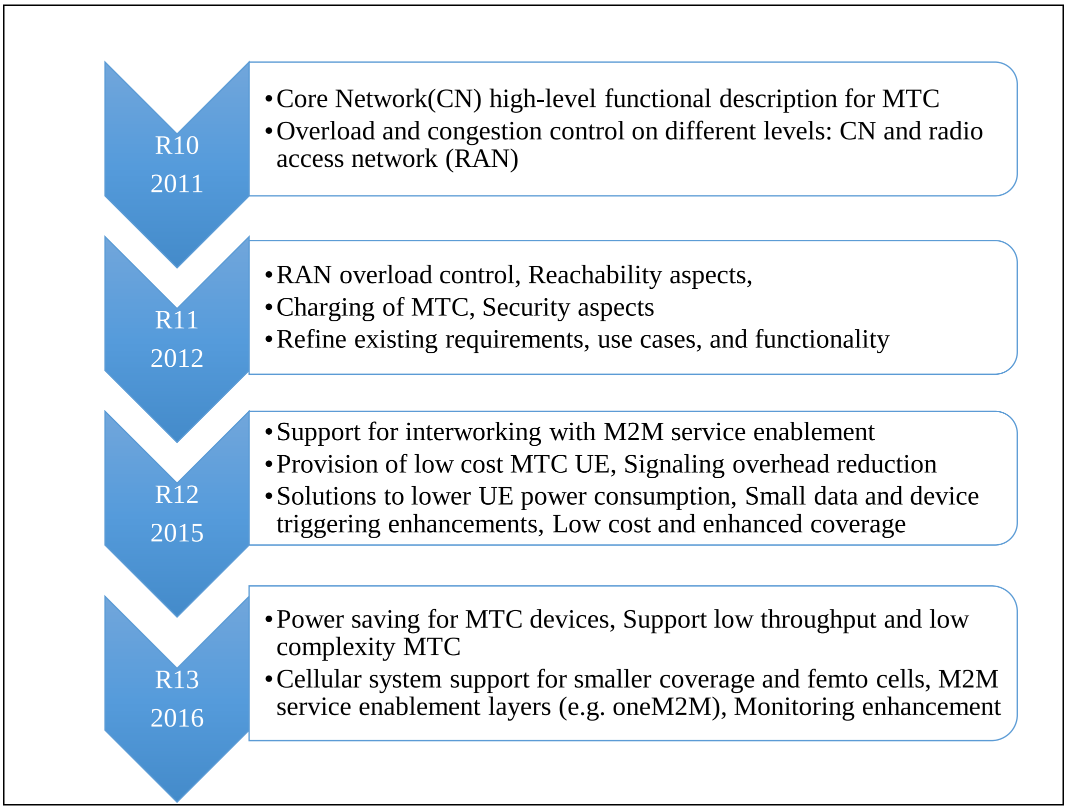


Figure 10: MTC Enhancements through LTE releases [34]

2.5.2 Issues Facing M2M Communication in LTE/LTE-A

With the expected growth in the number of M2M communications shown in Figure 1, it is essential to classify and investigate the challenges [6] that may face M2M communication over LTE networks, since LTE represents the coming generation of cellular networks.

1. Traffic Characteristics

The characteristics of M2M communication data traffic normally differ from those of human-to-human (H2H) data traffic [35]. M2M traffic comprises specific traffic schemes because of its special functions (e.g., data aggregation and observing) and requirements (e.g., strictly real-time-based traffic), whereas H2H traffic follows a specific data volume, session length, and interaction frequency. Traffic categorization is a significant issue in the planning and design of network structures. It is well recognized that traffic characteristics in wireless sensor networks depend mainly on the application scenarios. This problem can be tackled, as the issues of interest are related to the traffic flow inside the wireless sensor mesh itself. Complications start to arise when sensor nodes become parts of the general M2M communication system. In this case, the M2M communications will be complicated by the huge amount of data generated by sensor networks installed for heterogeneous services, which thus have widely varying traffic characteristics. M2M applications may produce unusual traffic schemes, such as event-driven signals, periodic signals, and media streaming. In addition, the M2M data packet is varied in size and consequently has various bandwidth requirements. In the case of video monitoring devices, data having a size of megabytes can normally be expected; in the case of small-sized sensor data (e.g., temperature and humidity), the amount of data per transmitted packet is usually small, and the measured data are reported at periodic intervals. Although these intervals may range from several minutes to hours, the aggregation of multiple M2M devices may form a noticeable dense node distribution scenario. Furthermore, the assignment of a single physical resource block (PRB) to an M2M sensor to transmit only a small amount data could degrade the spectral efficiency in the network to an extreme extent. In cases of emergency event-driven traffic, such as that related to fire and flooding, networks may have to handle simultaneous transmissions of emergency data. This can severely degrade the overall network performance and may cause resource blockage for other regular users. M2M traffic standardization is also required to allow a good QoS for the various M2M applications. The problem of spectrum allocation in LTE/LTE-A stations to support QoS for M2M devices remains a challenging subject for further research.

The direct utilization of the current LTE/LTE-A protocols may not fulfill the requirements of M2M communications because of the low latency associated with the wide bandwidth of LTE/LTE-A networks. Hence, a new perception of the transport layer is necessary for M2M applications with respect to LTE/LTE-A employment. The transmission control protocol (TCP) operated at the transport layer has been identified as being insufficient for M2M traffic for the following reasons [6].

• Signaling setup. Many M2M communication systems are used to exchange small amounts of data, and thus, the signaling phase incurs the addition of a significant unnecessary time portion to the session time.

• Congestion control. One of the main aims of the TCP is to allow end-to-end congestion control. On the one hand, in M2M communications in 3GPP LTE/LTE-A, the congestion issue may lead to the problem of poor performance, since the communication is executed by utilizing wireless mediums. On the other hand, if the amount of data to be exchanged is very small, TCP congestion control would be useless.

• Data buffering. TCP operation requires data packets to be saved in a memory buffer. The management of such a buffer may be not sufficiently efficient for the resource-constrained M2M devices.

• Real-time applications. TCP was not originally intended for real-time applications and it is not suitable for enabling real-time M2M wireless communication networks.

Therefore, the TCP congestion control mechanism requires a core enhancement in order to improve the TCP operation over LTE/LTE-A to the extent that it becomes suitable for M2M communications.

2. Routing Protocols

The primitive form of typical M2M communication systems is a sensor network employed for data sensing and collection applications and depends on low rate, low bandwidth, and delay tolerant data gathering processes. Promising research, such as scientific, military, healthcare, and environmental monitoring studies, has considered more sophisticated applications, where each M2M device executes various tasks, such as sensing, executing actions, and sometimes decision making. Therefore, the communication structure for the sensor nodes in M2M communication faces diverse difficulties in maintaining the different technical requirements of these applications. Furthermore, the applications mentioned above have different QoS requirements (e.g., delay, throughput, reliability, bandwidth, and latency) and also different traffic characteristics. Accurate and realistic information about rapidly changing situations must be captured in real time in order to effect an appropriate response at an appropriate time. The enablement of M2M sensing networks based on enhanced sensing devices and developed networking mechanisms is a promising solution for achieving such applications.

The use of wireless multimedia sensor networking (WMSN) is becoming more widespread because of its capability to support real- and non-real-time applications through extracting multimedia information by means of an intelligent and trustworthy class of sensor systems distributed worldwide [6].

However, for multimedia transmission, routing mechanisms fill a main role in satisfying the strict QoS requirements. Multimedia M2M applications are classified as resource-constrained, and they impose major challenges.

Despite the wide variety of routing protocols available, with regard to routing techniques the emerging demand for M2M services still presents challenges. These challenges arise in relation to single source and multiple sinks, multiple sources and single sink, multiple sources and multiple sinks, cross layer detection, multiple channel access, and mobility problems [6].

Current routing protocols are designed to cater for source-constrained applications and assume that data traffic parameters meet QoS requirements; thus, they concentrate on power consumption improvement. Therefore, routing techniques must be completely redesigned or at least improved in terms of QoS considerations to guarantee secure routing and QoS requirements based on source traffic.

3. Heterogeneity

Recently, the form of M2M wireless communication networks has come to be an integration of different wireless technologies combined to achieve the desired performance at minimum cost. This cost can be the economic, bandwidth, or complexity cost. For example, home-based sensor networks may use short-range wireless technologies, such as ZigBee and Symphony Link, to communicate with each other and with a nearby gateway, and then, the gateway may use another wide coverage technology, such as LTE, to deposit the data into the backend destination [23]. Moreover, as explained in the Introduction section, researchers are anticipating the deployment of new wireless access techniques. The results of research activity on the integration of accesses has made simultaneous data exchange through several interfaces (known as aggregation or multi-homing) possible [36], which forms another heterogeneous method.

Heterogeneous networking requires a 3GPP LTE/LTE-A network in order to be effective and capable of handling heterogeneous UEs and services and to be adaptable to technology integration. It also requires an immense variety of additional features at the UE domain, such as flexibility, storage ability, computational power, and compatibility with different integrated technologies.

4. Security

Several factors render M2M communications vulnerable to attack. First, the capability of M2M sensing nodes is limited because of the limitations in power and in their ability to handle complicated algorithms that support information security. Second, the sleep mode of the nodes' operation makes hacks untraceable by the system's monitors if the attack occurs when the node is in sleep mode. Furthermore, eavesdropping is more probable, since the M2M applications utilize wireless channels. Finally, MTC devices are unsupervised by humans, which facilitates physical attacks. These reasons and more make security an essential issue for reliable services in M2M communications [6].

2.5.3 Future Challenges to M2M Communication

There are several additional challenges and open research topics that need to be investigated in the future [6].

1) Spectrum utilization management. Spectrum scarcity is one of the most important issues to be considered in the deployment of wireless M2M networks [37]. The

development of heterogeneous networks is a promising trend in telecommunications, which is expected to significantly improve coverage area, power consumption, signal quality, and spectrum efficiency. Another serious issue that arises in relation to installing M2M systems over LTE/LTE-A is that the spectrum is shared with regular cellular subscribers and services (H2H communications), since it has been proved in practice that the spectrum is less efficient when shared [38]. This fact emphasizes that the development of spectrum efficiency must consider shared-spectrum settings for M2M systems.

2) Opportunistic access. This recent method relies on the detection of spectral holes and their utilization in dynamic access networks. It is also known as the cognitive radio technique [39].

Although this technique supports LTE/LTE-A enabled systems, including M2M applications, it requires the use of complicated technologies for detecting white spectrum holes and an efficient management protocol to prevent a cognitive radio resource from interfering with the regular users [6].

3) Connectivity. Another key concept in M2M systems studies is the provision of the various MTC devices with the capabilities required to ensure reliable connectivity in LTE/LTE-A. Connectivity is usually subject to antenna design, energy consumption, and the interoperation of different integrated technologies, e.g., multi-homing and the cognitive radio technique [40]. Therefore, adaptive mechanisms for a dynamic working plane must be one of the first requirements to be addressed. However, it should be stated that an over-connected system becomes difficult to manage because of increased interference [6], and thus, it is a rather critical to understand what elements of the system should be connected in order to provide the desired

communication capabilities for M2M devices. Moreover, the 3GPP LTE/LTE-A standards allow connections to base stations, referred to as eNBs in LTE Advanced, via single-hop links in H2H applications. However, utilization of single-hop connections may not be an applicable solution, given the distinct data traffic characteristics and huge number of devices in M2M systems, which creates another challenge for researchers of M2M as compared with H2H communications.

2.6 LTE Approaches to Tackle the Problem of Spectrum Scarcity

LTE technology has been considered as a key enabler for cellular M2M architectures. It is capable of providing an extensive support for MTC devices. However, supporting an increasing number of connected devices in the future of IoT will probably require going beyond the current operating frequency bands. Actually, this is extremely important, especially for the cellular architecture since the spectrum scarcity problem directly influences the reliability and the QoS offered by the network [3]. Three approaches have been investigated in this chapter in which it is focused to overcome the spectrum scarcity issue, Figure 11. Those approaches are: small cell design, interconnecting the cellular network to other wireless networks (Heterogeneous Networks), and Cognitive Radio (CR). They are considered to be promising solution for future MTC communication.

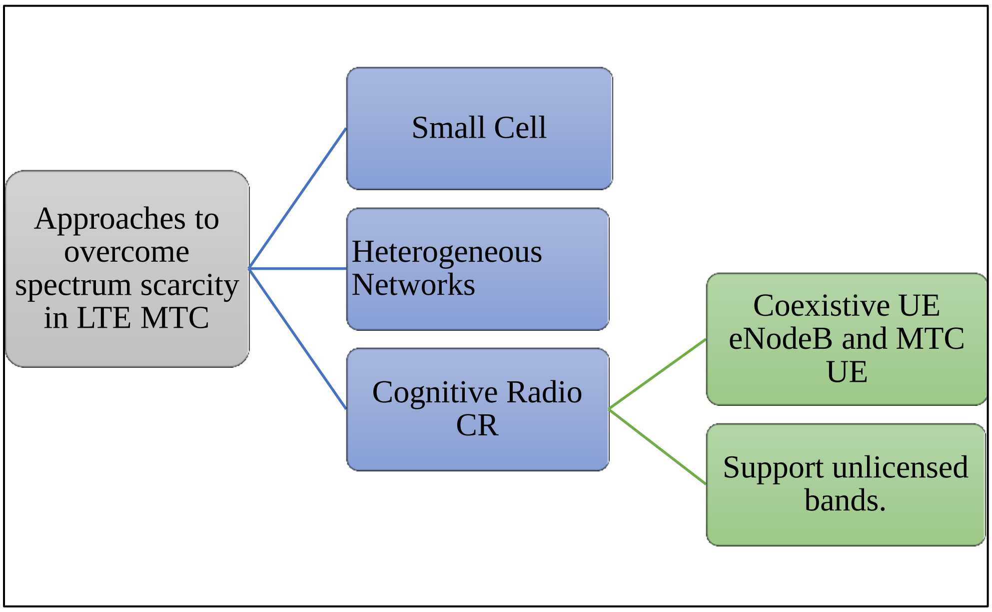


Figure 11: LTE approaches to tackle the problem of spectrum scarcity

2.6.1 Small Cell Technology

Cellular MTC networks in the next generation will need to provide an efficient interconnection to support the IoT. The traditional solution to accommodate the IoT is to create M2M technology over a small cell structured system. In this case, LTE cellular network providers need to deploy several thousand eNBs in the cellular context, each serving a smaller cell radius, instead of deploying only fully powered transmitters within large cells [36]. The eNBs are allocated to H2H communication or to MTC, both of which can communicate via the EPC connected to the cloud. Figure 12 illustrates the architecture of small cell technology. However, the deployment of such a huge number of small cells is limited by the co-channel interference factor. Moreover, complicated designs are needed to fulfill the desired QoS requirements. Furthermore, network management and signaling congestion will noticeably increase the traffic, adding a further disadvantage to this approach [3].

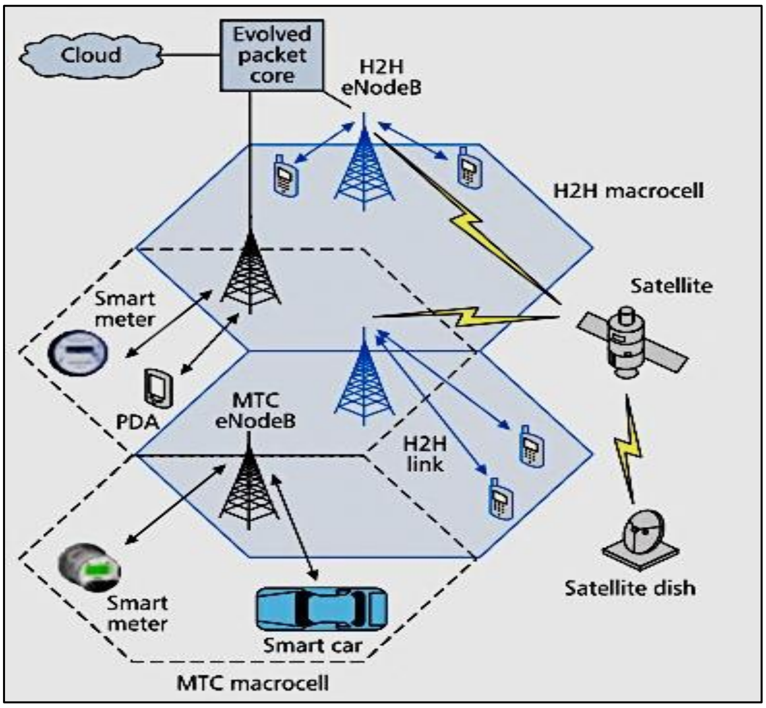


Figure 12: LTE small cell and CR solution architecture [3]

2.6.2 Heterogeneous Networks

Heterogeneity in networking concerns interconnecting the cellular network to other wireless networks to reduce the number of direct connections to the eNB. The source of the idea is the possibility of clustering machines geographically, where the members of each cluster can be interconnected together through a certain technology. Each cluster would nominate a cluster head to act as a representative (gateway), to connect with the cellular network and to be responsible for relaying the aggregated traffic of the entire cluster. Thus, the cellular network will be transparent to all machines inside the cluster and only the cluster head will be in contact with the eNB. For example, if all machines ae equipped with WiFi interfaces, then WiFi technology will be utilized to establish the connections between cluster members, including the cluster gateway, while the LTE interface will be used to communicate with the cellular network to reach the backend destination.

WiFi will be utilized [6] to collect data packets from cluster nodes and deliver them to the M2M gateway. The received packets will be stored in the buffer of the M2M gateway, taking into consideration that various types of data packets with different QoS requirements can be stored in distinctive buffers. In this approach, the LTE/LTE-A transceiver of the M2M gateway receives a head-of-queue packet from the buffer and transmits it to a 3GPP LTE/LTE-A eNB. After the data packets sent from M2M gateway are received by the eNB, they are forwarded to the M2M control center. The M2M server is located at the M2M control center for processing and storage of the received data. These data are used for the monitor, control, and command of the M2M devices [3].

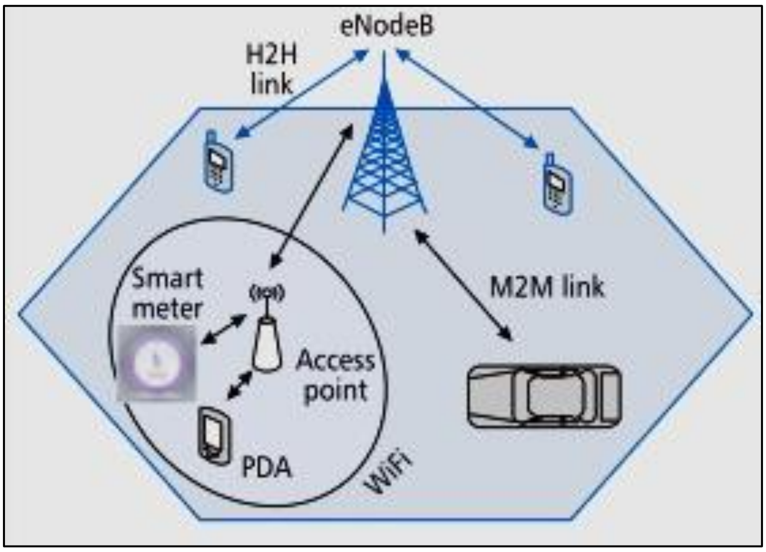


Figure 13: A heterogeneous cellular network model [3]

Figure 13 shows a heterogeneous cellular network model. In this model, the cellular network has offloaded part of its traffic to the individual clusters and therefore reduced the effective number of covered users. The elimination of congestion that would result when clusters are not formed is an important benefit of this approach.

2.6.3 Cognitive Cellular M2M Networks

To utilize the RF spectrum more efficiently [37], there are two approaches to applying the CR concept in cellular M2M networks. The first approach is to relax signaling congestion and management load; it assumes that there can be two types of eNB coexisting with each other, one for typical UEs and a second for MTC UEs. In this approach, M2M devices are given the opportunity to access the spectrum when the H2H devices are idle. This means M2M and H2H devices are not allowed to operate over H2H links simultaneously. This can be achieved by coordinating the corresponding eNBs. When a radio resource is occupied by M2M communication, it is considered to be experiencing server interference and is not utilized by H2H communication. Although this approach is simple to apply, it can degrade the QoS of H2H applications, in particular when the number of MTC devices is very large. To tackle these problems, a second approach was proposed in [3].

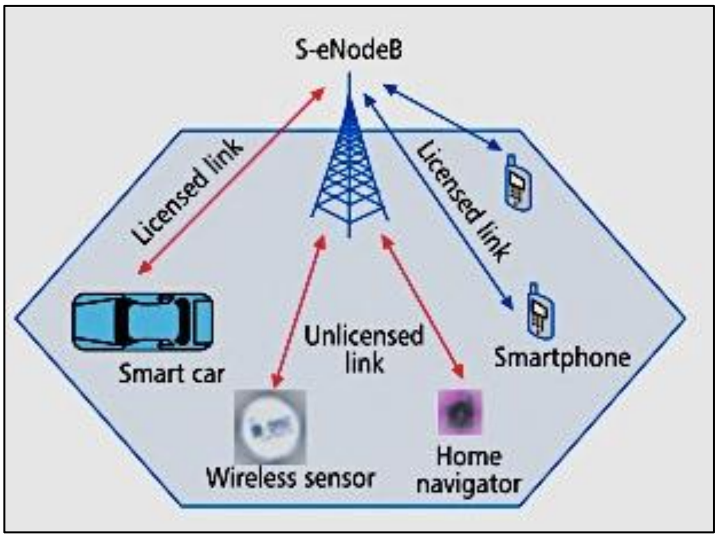


Figure 14: A cognitive cellular network model [3]

It supports sensing to find extra vacant unlicensed bands in addition to existing licensed bands. For this purpose, it is proposed that a smart-eNB (indicated as an S-eNB) be implemented, if complexity permits. More than one unlicensed band in a cell can be utilized by it, as shown in Figure 14.

Chapter 3: System Model

In this chapter, the design of the proposed M2M system is discussed and explained in detail. The communication architecture elements, standards, and protocol operations are examined as a platform for the simulations. The system topology, components, layered architecture, and propagation model are discussed.

3.1 Problem Statement

M2M communication applications are expected to be widely deployed in large numbers throughout the different technology fields in the near future. M2M communications over cellular networks present significant challenges on any cellular technology because of the different M2M data characteristics, data transactions, diverse applications, and the large number of connections. In addition, existing communication standards and protocols are not competent to provide a sufficiently satisfactory performance for M2M traffic [21]. The handling of large numbers of M2M terminals to be supported by cellular networks poses many obstacles, some of which have been removed by the use of capillary M2M [21]. When a number of machines are able to form clusters, the data can be aggregated and managed by a gateway, and then, the load on the cellular network becomes light. The gateway has the ability to collect and reshape M2M traffic for further transport to the related M2M servers. This aggregation is accomplished mainly by the capillary gateway as an intermediate node that heads a group of M2M nodes known as a cluster. However, some M2M applications are considered demanding in terms of bandwidth, require high data rates, which cannot be easily supported by cellular networks, and are given priority over human-based communications. Therefore, the spectrum management will be a focal challenge in the future for enabling M2M applications in 4G cellular networks such as LTE. In addition, it is well known that capillary M2M systems suffer from poor reliability and unbounded packet delay [22].

3.2 Network Topology and Proposed Solution

A single-cell multiuser scenario is considered with a full coverage of 3GPP LTE and WiFi. LTE and WiFi are used in combination to form a heterogeneous network. The sensing nodes involved in the M2M communication are MTC devices and can be clustered. The nodes are of two types. Type A is a real-time transmission MTC device with a high data rate and Type B is for non-real-time transmission of only small messages. All nodes are clustered; each cluster contains a number (N) of MTC devices to communicate with a capillary gateway, assuming that a cluster contains only one type of node, that is, either Type A or Type B. The data collected by the sensing nodes are transmitted to the M2M management server through the heterogeneous capillary gateways. Each capillary gateway is a head of a cluster located in a building and assumed to be static (non-mobile). The effect of the connection between the clustered sensing nodes and the capillary gateway in our model is out of the scope of the thesis study.

In this thesis, we outline some advances that will enable existing M2M services over capillary networks, in conjunction with existing LTE cellular communication standards and WiFi technology, to be adapted to the requirements of M2M traffic. A heterogeneous M2M network architecture is proposed and its performance is analyzed using extensive computer simulations. The network is considered to be heterogeneous, since the capillary gateway transmits data through an LTE interface and a WiFi interface in parallel. Two main outcomes are expected if the capillary gateway is capable of aggregating data from cluster nodes and forwarding it to the M2M server using both technologies, LTE and WiFi. First, the bandwidth provided will be utilized more efficiently; second the packet delay will be reduced. Figure15 illustrates the topology of the modeled network with the technologies used.

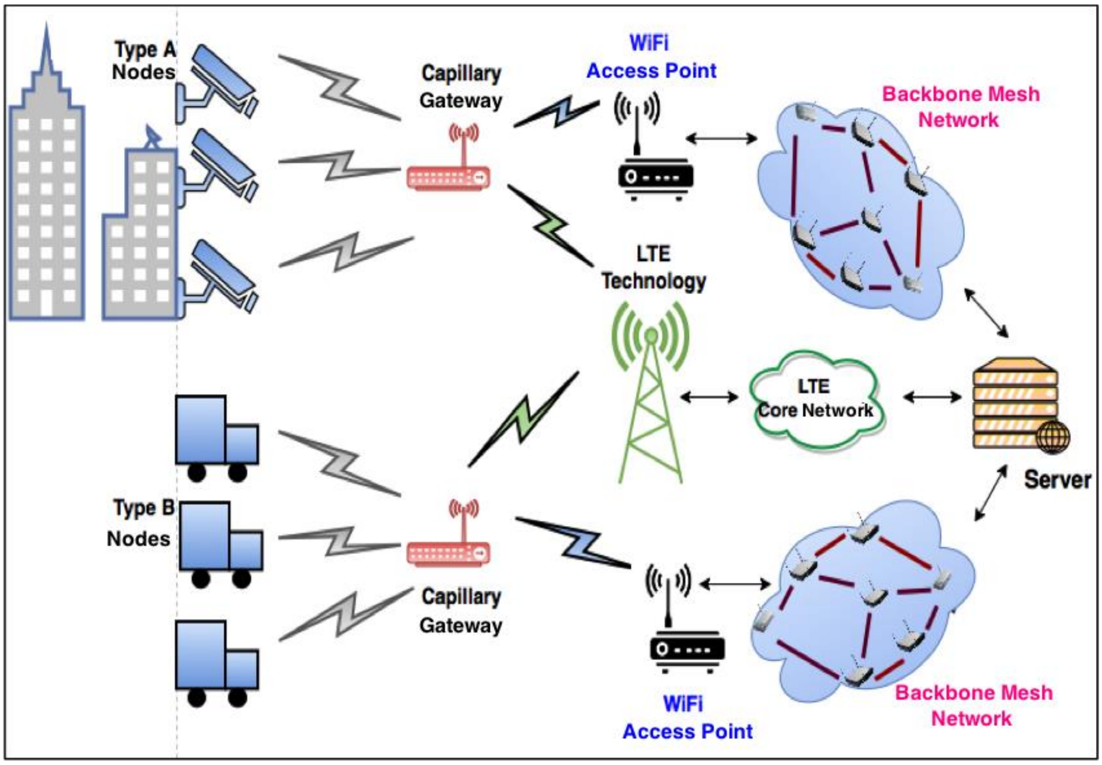


Figure 15: System topology

In the proposed architecture, the capillary gateway aggregates data from clustered nodes. Packets are forwarded to the M2M server. The main function of the capillary gateway is to manage the shared traffic according to certain parameters, which are investigated in the simulation. Packets are grouped and transmitted to the LTE base station (eNodeB) and to the WiFi access point. The LTE network then communicates with the M2M server via the PDN gateway. We propose connecting the WiFi access points using a WiFi-based mesh network backbone as a cost effective way of extending the coverage of the WiFi network. This backbone forwards the data to the management server using an ad hoc on-demand routing protocol. The choice of the suitable routing protocol is done through a comparative simulation study between two widely adopted ad hoc routing protocols, namely, distance vector (AODV) and dynamic source routing (DSR) protocols. . The proposed architecture is flexible to accommodate multiple management servers for load balancing and fail-safe redundancy. An investigation for the impact of the number of servers on the QoS parameters is conducted.

3.3 Layered Architecture

The design of the system model involves networking layers, as illustrated in Figure 16. In this section, the propagation model for the physical layer is discussed. For the data link layer, LTE and WiFi technologies are discussed; version IEEE802.11 is used in the simulation. Different routing protocols for building the network layers are compared. Finally, the user datagram (UDP) is explained as a transport layer protocol.

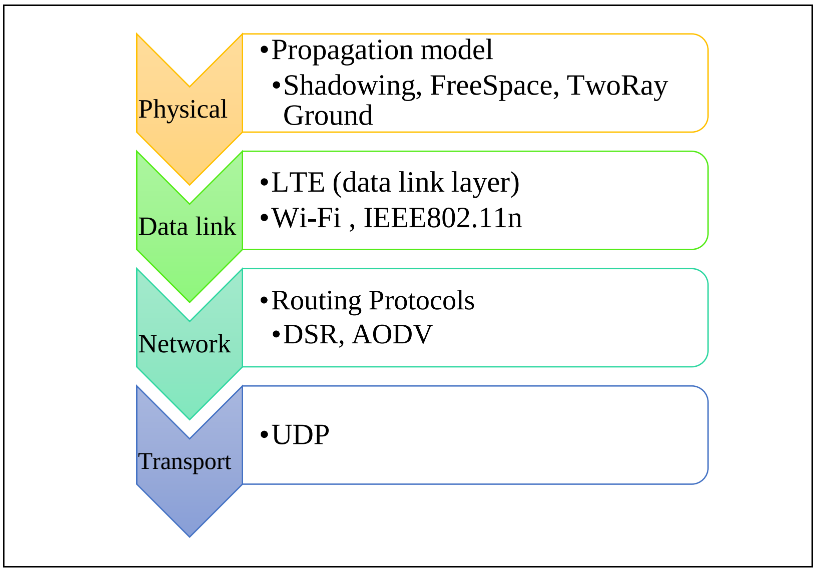


Figure 16: The layered system model

3.4 Propagation Models

A radio propagation model, called the Radio Wave Propagation Model, is used to depict the physical layer in a wireless communication network by estimating the effect of the main characteristics of the radio channel, such as path loss (PL), fading, and shadowing. These physical parameters are dependent on the positional geometric relationships between the transmitter antenna, the receiver antenna, and the surrounding physical atmosphere.

PL is a quantity of the average RF attenuation that a transmitted signal suffers until it arrives at the receiver, after traversing a path of several different wavelengths. It is expressed by [41]

$$PL(dB) = 10\,log\frac{P_t}{P_r} \tag{3}$$

where P_r and P_t, are the transmitted and received power, respectively.

Two main types of models are used to characterize PL. The first type comprises statistical (or empirical) models and the second deterministic (or site-specific) models. The former are based on the statistical description of the received signal. They are easier to implement, entail less computation, and are less affected by the environment's geometry. The latter have a firm physical basis, and require a massive amount of data related to geometry, topography profiles, locations of building and of different materials in buildings, and so on. These deterministic models apply more computations, and therefore, are more accurate.

The deviation of the attenuation affecting a signal over certain propagation media is known as fading. The fading amount generally varies with time, radio frequency, and geographical position. It is often modeled as a stochastic progression. Fading is categorized as large-scale and small-scale fading. Large-scale fading arises because the signal's travel over large areas is affected mainly by the presence of hills, woodland, and buildings between the transmitter and the receiver. Small-scale fading occurs because of minor variations in positions.

For the outdoor scenarios in both macro-cell and microcell systems, there are a number of suitable empirical (statistical) models, such as Okumura et al.'s model, which is considered one of the simplest and best in terms of precision in estimating PL, and is commonly used in urban areas in cellular systems. The Hata Model and the Dual-Slope model, which is based on a two-ray model, are considered appropriate for large-cell mobile systems.

Fading channels usually have a significant negative effect on network QoS as compared to non-fading channels [42]. In our simulation, we considered three models: the Free Space model as a non-fading model, the Two-ray Ground model, and the Shadowing model, to evaluate the propagation model effect on QoS in the proposed architecture.

3.4.1 Free Space Model

In the free space propagation model, it is assumed that the propagation condition is ideal, which means there is only one direct line-of-sight (LOS) path between the transmitter node and the receiver. The power of the signal received at the receiver antenna, which is separated from the transmitting antenna by a distance d, is given by the Friis free-space equation [41]:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\Pi)^2 d^2 L} \quad (4)$$

where G_t, and G_r, are the gain of the transmitting and the receiving antenna, respectively, L is the system loss factor, not related to propagation, and λ is the wavelength in meters. Therefore, PL (in decibels) can be expressed as [41]

$$PL(d) = PL(d_0) + 10\beta \log \frac{d}{d_0} \quad (5)$$

where β = 2 describes a free space. However, the value of β is usually higher for wireless channels. PL is the basic component of a propagation model. It is related to the coverage area of the network. d_0 is a reference distance.

3.4.2 Two-ray Ground Model

A single LOS path between two communication nodes is not a realistic means of propagation. A reflection model that considers both the direct path and a ground reflection path is known as a two-ray ground model. This model attempts to achieve a more accurate prediction for a long distance than that of the free space model. The predicted received power at distance *d* is calculated by [41]

$$P_r(d) = \frac{P_t G_t G_r {h_t}^2 {h_r}^2}{d^4 L} \quad (6)$$

where h_t and h_r are the heights of the transmitter and receiver antennas, respectively. The two-ray model does not present an acceptable path estimation for a short distance because of the oscillation caused by the constructive and destructive combination of the two rays. Thus, the free space model is still preferred when *d* is small.

3.4.3 Shadowing Model

Both the free space model and two-ray model forecast the received power as a deterministic function of the distance traveled. They both represent the communication range as an ideal circle. However, in reality the power received at a certain distance is a random variable that varies with multipath propagation effects, also known as fading effects. In fact, the above two models estimate the mean received power at distance *d*. A more general and widely used model is called the shadowing model, which is more realistic since it augments the estimation to include a random component that attempts to regenerate a typical random variability of wireless links (e.g., fading).

The shadowing model is comprised of two measures. The first is known as the PL model, which also estimates the mean power received at distance d, denoted by $\overline{P_r(d)}$. It uses a close distance, d_0, as a reference. $\overline{P_r(d)}$ is computed relative to $P_r(d_o)$ as in (7) [41]:

$$\frac{\boldsymbol{P_r(d_o)}}{\overline{\boldsymbol{P_r(d)}}} = \left(\frac{\boldsymbol{d}}{\boldsymbol{d_o}}\right)^{\boldsymbol{\beta}} \quad (7)$$

β denotes the PL exponent, and is typically determined by field measurements; $\beta = 2$ for free space propagation and 2.7 to 5 in shadowed urban areas. d_0 is a reference distance.

The second part of the shadowing model imitates the variations in the power received at a certain distance. It follows the Gaussian distribution, and it is measured in dB. The overall shadowing model equation is represented as [41]

$$\left[\frac{P_r(d)}{P_r(d_o)}\right]_{dB} = -10\, \beta\, log\left(\frac{d}{d_o}\right) + X_{dB} \quad (8)$$

where X_{dB} is a Gaussian random variable with zero mean and standard deviation σ_{dB} = 4 to 12 in outdoors environments. d_0 is a reference distance.

In our simulation the default constant parameters of NS2 are considered, and these are d_0= 1 m, $\beta = 2$, σ_{dB} = 4.

3.5 LTE-A

LTE originated in a project conducted in 2004 by a telecommunication entity known as the 3GPP. The main objective of LTE is to provide packet-optimized radio access technology supporting flexible bandwidth deployments, a high data rate, and low latency. The design of the network architecture was aimed to support packet-switched traffic with perfect mobility and extremely good QoS.

3.5.1 LTE Features

It is expected that LTE will achieve higher data rates in the future: a 300 Mbps peak downlink and 75 Mbps peak uplink. In a 20 MHz carrier, data rates greater than 300 Mbps can be achieved under very good signal conditions. LTE is an ideal technology for supporting services that demand high data rates, such as voice over IP (VOIP), streaming multimedia, video conferencing, or even a high-speed cellular modem. This is suitable for our system model, since we assume real-time video streaming and voice file transfer. LTE uses orthogonal frequency division multiplexing (OFDM) for the downlink, that is, from the base station to the terminal, to transmit the data over many narrow band carriers of 180 KHz each, instead of spreading one signal over the entire 5 MHz carrier bandwidth; i.e., OFDM uses a large number of closely spaced subcarriers for multicarrier transmission to carry data. All LTE devices have to support MIMO transmissions, which allow the base station to transmit several data streams over one channel simultaneously. This reduces the unwanted impact of M2M communication on H2H communication over LTE networks.

3.5.2 LTE Architecture

The high-level network architecture of LTE comprises the following three main components:

I. UE. In our system, the UE is the capillary gateway.

II. The evolved UMTS terrestrial radio access network (E-UTRAN), which has one type of component, the evolved base stations, called eNBs. The capillary gateway communicates with only one base station and one cell at a time. Two main functions are supported by the eNB; the eNB sends and receives radio transmissions to all the UEs using the analogue and digital signal processing functions of the LTE air interface and controls the low-level operation of all its UEs, by sending them signaling messages.

III. The core network. The architecture of the full EPC is illustrated in Figure 17.

The home subscriber server (HSS) element contains the required information about all the network operators' subscribers. The packet data network (PDN) gateway (P-GW) is the part that communicates with the outside world. The serving gateway (S-GW) performs as a router and forwards data from the base station to the PDN gateway. The mobility management entity (MME) controls the high-level process of the mobile device by means of signaling messages and the HSS.

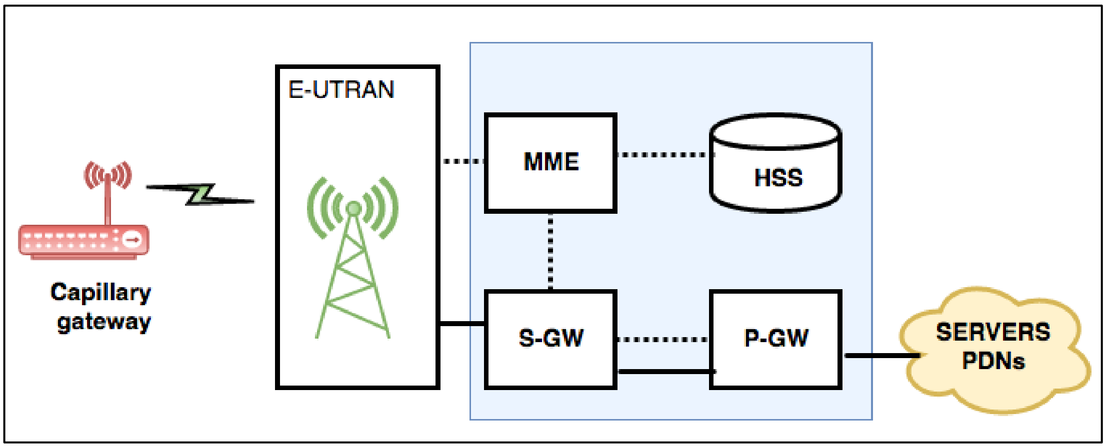


Figure 17: The architecture of evolved packet core (EPC) in LTE

The interface between the S-GW and the P-GW is known as S5/S8. This has two slightly different accomplishments, namely, S5, if the two devices are in the same network, and S8, if they are in different networks. In our system model, the PDN gateways communicate with the M2M data management server.

3.6 The WiFi Network

WiFi is the name of a wireless networking technology that provides high-speed networking and Internet connections by using radio waves. It depends only on RF and involves no physical wired connection between the sender and the receiver.

The access point (AP) is considered to be the cornerstone of any wireless network. The essential function of an AP is to broadcast a wireless signal that wireless devices can detect and tune into. Many cities around the world in the early 2000s adopted plans to build citywide WiFi networks, and many of them, such as South Korea's capital, were successful.

3.6.1 IEEE802.11n

The version of the WiFi standard assumed in our system model is IEEE802.11n. This version contains improvement amendments of the previous 802.11 standard by including MIMO antenna technology and it has a wider outdoor range, up to 250 m. MIMO technology qualifies the system to set up multiple data streams on the same channel, thus increasing the data capacity of a channel. Table 2 shows the main parameters of the standard according to a Cisco data sheet [43].

Table 2: IEEE802.11n parameters

Parameter	**IEEE 802.11n Standard**
Maximum data rate (Mbps)	300
RF Band (GHz)	2.4 or 5
Modulation	QAM / OFDM
MCS indexes	0,1,2,3,4 …… to 15
Channel width (MHz)	20, or 40

To provide the various parameters required, the modulation used in this WiFi standard is OFDM. It is a form that uses a large number of closely spaced carriers that are modulated with low rate data. The closely spaced signals would normally be expected to interfere with each other; however, the signals are taken orthogonal to each other to allow no possibility of mutual interference. The advantage of the IEEE 802.11n standard is that it adds a major enhancement in the speed at which data can be transferred over a wireless network. Although this may not be required for several small networks where small files are being transferred, the amount of data being transmitted over most networks is growing rapidly with considerably more large files, including photos, videos, etc., being transmitted. The new 802.11n standard is able to meet the challenge of providing the desired capacity for wireless or WiFi networks..

3.6.2 Backbone Mesh Network

The capillary gateway is directly connected to the WiFi access point. We propose that different WiFi access points are able to forward the data from capillary gateways to the M2M management servers through a cost-effective WiFi-based mesh network. A wireless mesh network (WMN) is a communication network that consists of radio nodes systematized in a mesh topology. It is also a form of wireless ad hoc network. WiFi-based mesh networks are typically contain mesh routing nodes (routers) and boarder gateways. If one of the mesh nodes can no longer operate, the other nodes in the mesh cloud continue to communicate with each other, directly or through one or more transitional nodes. Mesh networks can usually be fully or partly connected. However, since the number of required connections grows considerably with the number of nodes for full mesh networks, this is considered impractical for large networks. Therefore, the proposed M2M wireless mesh backbone is a partially connected network, where some of the nodes are connected to exactly one other node and some other nodes are connected to two or more nodes with a point-to-point link, as shown in Figure 18. This ensures that the expense and complexity required for achieving a connection between every node in the network is avoided, and the connection between nodes that are not directly connected is through routing operations via protocols.

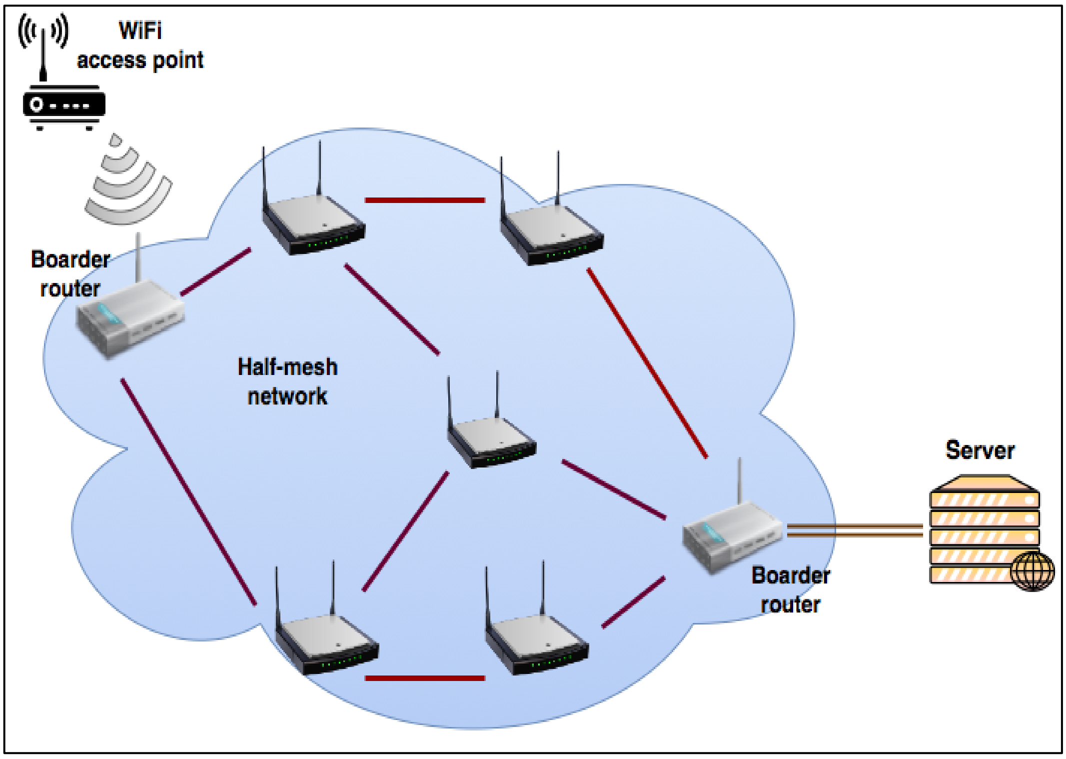


Figure 18: Mesh cloud diagram

3.6.2.1 Routing

In the described mesh cloud, the packets are forwarded along pre-computed shortest paths between the routers to reach the gateway located on the boarder of the cloud. The border gateway is considered directly connected to the M2M server. Routing protocols are used to compute the shortest path or the least cost path. The cost of a path is defined as the accumulated cost of its links. This cost can be a value inversely related to bandwidth or a value related to congestion real cost [44]. Ad hoc routing protocols are classified into three basic categories: reactive routing (on-demand), which maintains a route to the destination based only on connection demand; proactive routing, which maintains up-to-date routing information at any time; and hybrid schemes. The AODV and DSR routing protocols are examples of reactive protocols and the destination-sequenced distance vector (DSDV) protocol is an example of proactive protocol.

In AODV, links between nodes are assumed to be bi-directional (symmetric). If a node has no defined route to another node, the first node starts a route discovery process by flooding a route request (RREQ) message. Every node re-broadcasts an RREQ and sets up a reverse path indicating the source node until the anticipated destination receives the RREQ. The latter replies by sending a route reply (RREP) message, which follows the set-up reverse path. After a timed-out interval, the forward path and the reverse path are deleted if not used for a certain time interval.

In DSR, if a node has no known route to another node, it initiates first a route discovery by flooding an RREQ message. Every node in the cloud includes or attaches its identifier (node ID) when forwarding the RREQ packet. The destination node replies with an RREP when it receives the first RREQ. This RREP travels on a route obtained by reversing the route maintained by the nodes that received the RREQ. DSR is known for routes caching, where every node caches the new route it learns, even when it is only forwarding data or overhears data packets. DSR operation depends on the entire route that is included in the header of the packet sent from the source. For this reason, this protocol is known as source routing.

In this research, the area of the mesh network, the routing protocol, and the routers density are expected to affect the QoS of the system. The packet delay and loss are observed by simulating different scenarios in the wireless mesh backbone part.

3.6.2.2 Media Access Control

The system performance in the wireless mesh backbone depends also on the IEEE802.11 MAC layer operation [45]. IEEE 802.11 carrier sensing is performed in both the MAC sublayer, known as virtual carrier sensing, and at the physical interface. The concept of the CSMA/CA multiaccess technique assumes that the medium is a synchronous multi-access bit pipe with packet transmission time slots that can be distinguished from idle time slots. If a node can detect idle time slots quickly, it is reasonable to terminate an idle time slot to allow nodes to initiate packet transmission after the detection of the idle time slot. A source station sends an MPDU to perform the virtual part of carrier sensing. The MPDU duration information is located in the header of data packets, RTS, and CTS. In the duration field, the stations use the MPDU information to adjust their network allocation vector (NAV). The NAV indicates the amount of time that should pass until the current transmission session is complete; then, the channel can be sampled again to determine its status. RTS and CTS are control frames used by stations to reserve channel bandwidth before the transmission of an MPDU. When a station receives error-free frames, an ACK is sent. The sender station interprets the non-arrival of an ACK as a loss, and executes a back-off interval before it retransmits the data packet. Receiving stations use sequence numbers to detect duplicate frames.

The IEEE802.11 MAC mechanisms mentioned above require certain conditions to provide a good QoS in the network. In our simulation, we examined how different variations (e.g., WiFi rates, propagation models, etc.) affect the performance of the ad hoc MAC layer, which definitely impact the packet delay and PL in the system..

3.6.3 User Datagram Protocol

The UDP is one of simplest transport layer communication protocols available among the transmission control protocol/Internet protocol (TCP/IP) suite. It involves a minimum amount of communication mechanisms. The UDP uses IP services, which provide the best effort delivery mechanism. TCP is connection-oriented and slow, but provides guaranteed delivery and preserves the order of messages, while UDP is a connectionless protocol that does not guarantee the ordering of packets, but is fast. Thus, UDP is suitable for real-time communications, such as video conferencing and voice over IP. It is called a user datagram, as the message of the user is not divided into packets and reassembled, as in TCP. Because of the real-time requirement of video streaming, TCP is not used and instead the UDP is used as a transport protocol. The UDP has a big advantage in that it provides fast video transmission; however, it is infamous for its PL, delay, jitter, and out of order packet delivery, which affects the video quality [46]. In our simulation, we observed the packet delay and packet loss in an M2M scenario, where video transmission is considered and expected to be affected by the transport layer protocol used.

Chapter 4: Simulation Results and Discussion

In this chapter, the details of simulation model are described and the results are presented.

4.1 Characteristics of MTC Data

Some guidelines have been considered before choosing the data packet sizes for the simulation, because the MTC data traffic is significantly different from the traditional data traffic [47]. MTC traffic usually consists of small amounts of data, usually a few hundreds of bytes (small sensor data, e.g. temperature, humidity etc.) accompanied by comparatively large signaling overhead if attempting to connect to an LTE mobile network. The big number of sensors in the network in this case causes a huge traffic. In contrast, some futuristic applications like real time surveillance causes also a huge traffic because of the high transmission data rate although the number of devices in the network is few compared to sensors networks.

In our simulation, it is assumed that all the devices can be grouped to form capillary clusters. A large number of devices is considered to be inside the capillary clusters and connected to less number of capillary gateways. Those devices are supposed to send data frequently, or in real-time; no mobility is assumed. The nodes in our simulator are the capillary gateways. To ensure the high density of the M2M nodes, the simulation considered a limited area for the capillary head nodes regardless to the full dimensions of the system area. This point is further detailed in the section of simulation model.

4.2 Simulator Used

Network Simulator-2 (NS-2) is used in this research to simulate the multi-homed capillary nodes and the multi-homed servers as well NS-2 is a discrete event simulator for computer networking research. It provides substantial support for simulation of TCP, routing, and multicast protocols over wired and wireless (local and satellite) networks and is largely used for research and educational purposes. NS-2's accuracy is commonly acknowledged in the academia and research community.

4.3 Simulation Model

4.3.1 Scenario and Topology

In the simulation we consider a typical M2M scenario of an area of one LTE cell with a full coverage of WiFi. It is running in a two-dimensional area X*Y m^2, which is split into three sectors, each has a specific type of nodes. The sectors can be categorized as:

- The first sector includes the capillary gateways as transmitters located in an area of 100*Y m^2.
- The middle sector includes the ad-hoc multi-hop routers located in an area of 100*100 m^2, and it is varied when observing the routing protocol effect. This sector is referred to as BKRT (Backbone routers).
- The last sector contains the data management servers as final destination in an area of (X-200)*Y m^2.

The area topology and different nodes dimensional distribution are illustrated in Figure 19. The dimensions of every sector are taken according to the transmission range of the network node, which is 250m.

The source of data packets is the capillary gateways nodes, while the final destination is the servers. Each of these network nodes is simulated as a multi-homed node that is connected to LTE and WiFi networks by two different physical interfaces.

The data packets transmitted through WiFi are proposed to reach the management servers over multi-hop mesh network, whereas a single hop is emulating the packets transmitted through LTE. For the sake of comparison, two different on-demand ad-hoc routing protocols are used in the simulation.

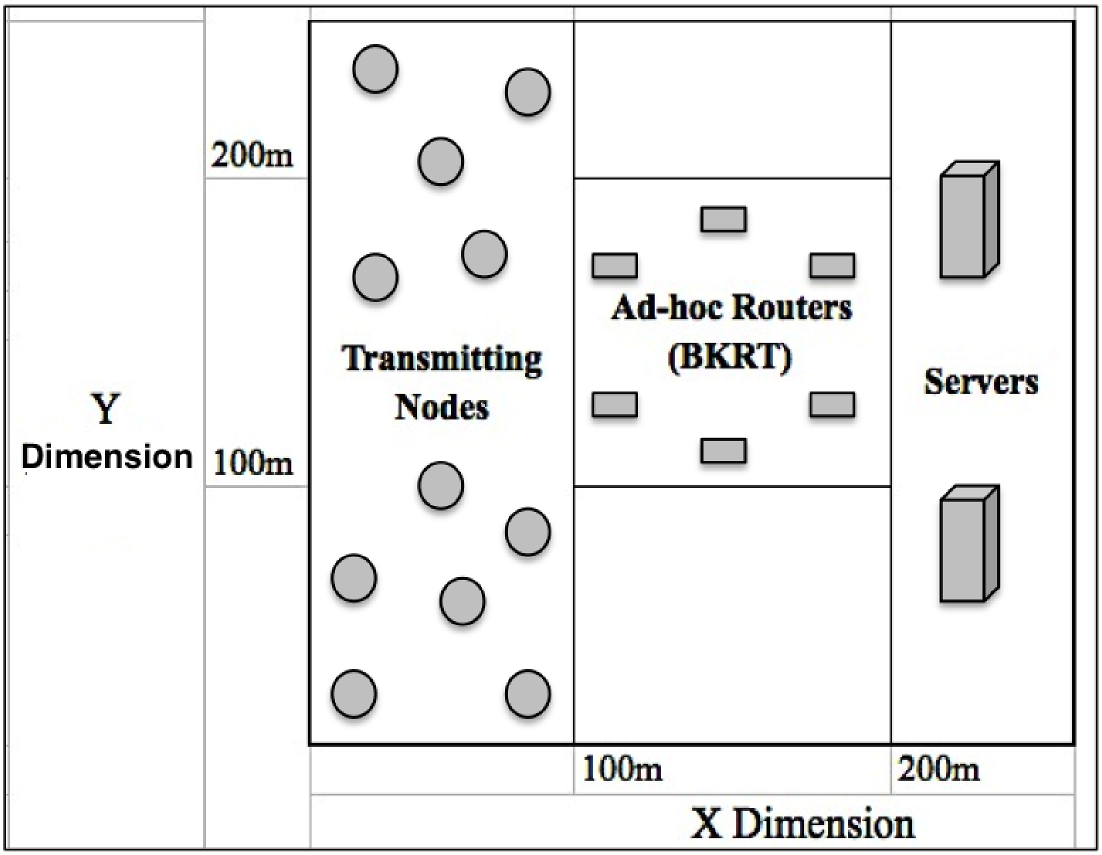


Figure 19: Area topology and dimensional distribution

With a single LTE base station connecting the simulated capillary gateways, and limited number of backbone routers, our scenario is expected to witness severe amount of MTC traffic. This traffic is caused by either a huge number of sensors like several tens of voice sensors or several hundreds of environmental or metering sensors communicating with the capillary gateways; or a few number of higher data rate devices like surveillance cameras. These devices all are trying to send data to the same destination (management servers) at the same time. In this research, we try to evaluate the proposed system performance under the aforementioned conditions.

4.3.2 Specific Simulation Presets and Parameters

All the devices send at the same instance. The total number of packets sent depends on the simulation time ranged in 100-200 seconds along with average source rate. The data packet size is set to be 1000 Bytes, the interval time is given by (9) [39].

$$\text{Time interval} = \frac{\text{Packet size} * 8}{\text{Average source rate}} \tag{9}$$

The average number of packets sent by the network also helps in evaluating the network performance; it is given by the (10) [22]:

$$\text{Average number of packets sent} = \frac{\text{number of capillary gateways} * \text{average source rate} * \text{simulation time}}{\text{packet size}} \tag{10}$$

Transmission nodes are all capillary gateways sharing the medium, WiFi and LTE. The fixed number of capillary gateways is taken according to the offered LTE channel rate. Referring to [5], the 4G future radio access is anticipated to provide data rates up to 100 Mbps and 50 Mbps for downlink and uplink respectively [48] with wide-area coverage. This peak rate is provided per cell and assumed to be shared fairly (equally) between all nodes in the cell. Hence, the LTE transmission rate per node in the simulation scenario is 2-5 Mbps since the number of capillary gateways can be up to 20 gateways. WiFi transmission rate is fixed as 54 Mbps [49] per cell in all simulations unless otherwise noted. The source rate does not exceed the transmission rate of LTE or WiFi, assuming the service in the respective cell is efficient. The network dimensions are 250x250 m^2, the number of data management servers is 2, and the simulation time is 100 seconds unless otherwise is mentioned. The simulation results evaluate the overall QoS under different variations of network parameters. The evaluation is implemented by measuring the average packet delay and the average packet loss in different scenarios to determine the impact of every variable in the network. The comparison is based on the fact that the guideline in conferencing videos is to have a packet delay not more than 150ms and a packet loss not more than 1% [50].

As the research considers real time video transmission applications, an online network IP security camera system bandwidth calculator [51] is used to determine the source rate of the capillary gateway in the simulations. According to the mentioned calculator, if the capillary cluster contains 2 to 4 cameras, the required bandwidth for the gateway is 1 to 1.2Mbps, if the quality of the video is medium, the camera resolution is 1Megapixel, and the codec used is MP4 with 2 frames per second. For this reason, the capillary gateway source rate varies from 1 to 2Mbps.

- As explained in the system model, the simulated network assumes a single cell over a squared area of 250*250 m^2 unless otherwise is mentioned. The antenna model is Omni antenna and every source node and server node has two physical wireless interfaces, namely, WiFi and LTE. WiFi transmission rate is 54 Mbps per cell, whereas LTE transmission rate is varied from 2 to5 Mbps per node. The radio propagation model is Free Space, and compared in some simulations with Two-ray Ground, and Shadowing models. The interface queue type is drop tail with 50 packets maximum queue size. The multiple access protocol in the data link layer is IEEE 802.11 for the WiFi. The packet size is 1000 Byte. NOAH protocol is used for the data transmitted by LTE, since no multiple hopes required, while AODV or DSR is used for data transmitted by WiFi through the BKRT. The BKRT network consists of 10 routers in an area 100x100m^2 unless otherwise is mentioned. The protocol of transport layer is UDP. The traffic sources follow exponential traffic model.

4.4 Simulation Results

4.4.1 Proposed Network Architecture Evaluation

Our proposed architecture provides capillary gateways and management servers by two interfaces of LTE and WiFi technology to improve the M2M services. In order to evaluate the outcome of our proposed architecture, we evaluate the performance of our architecture compared with the usage of single interface nodes. The evaluation is done under WiFi data rate fixed at 54Mbps per cell [52], and LTE data rate is fixed at 2Mbps per node.

A. WiFi Interface Only

In this simulation, the network includes an increasing number of capillary gateways such as 5, 10, 15, 20, 25 each of 1Mbps source rate. In Figure 20, in the case of nodes with WiFi single interface, the average packet delay is extremely higher than that with multi-homed nodes. It is ranged in 15ms to 1.72sec, which is incomparable with a range of 2-322ms in the case of multi-homed nodes. Also the loss results of two cases are compared in Figure 21. The loss is acceptable only for 5 capillary gateways, 0.083%. However it increases dramatically from 8% to 82% for 10 to 25 capillary gateways. The system performance deteriorates and becomes unreliable if it is run on WiFi technology only. The high packet delay and packet loss leads to acceptable QoS level only for small number of capillary gateways compared with the usage of multi-homing. . To interpret these results, the performance of 15 capillary gateways scenario is investigated.

For 15 gateways and source rate 1Mbps the total number of packets to be transmitted in 100 seconds is 187,500 packets. Having WiFi interface means 187,500 packets will be served through only WiFi channels, causing longer queues in the transmitting nodes and consequently delayed or dropped packets. Moreover, all the packets transmitted have to be routed through the mesh network that becomes overloaded with this huge number of packets causing the routers queues to overflow.

Another source of packet delay in the case of WiFi single interface is the delay occurs in the MAC layer. When a big number of packets are to be served, more collisions are expected and consequently more retransmissions (longer transfer time), especially that the MAC protocol IEEE802.11 doubles the back off interval when a collision happens to avoid more collisions. This mechanism may accumulate the delay in the transmitters side and in the mesh backbone network. In terms of packet loss, dropped packets are considered after consecutive collisions as per IEEE802.11 collision avoidance mechanism, which explain the increasing loss when the load is increasing. The delay and loss values in that case are 1.6sec and 59%

respectively, which means that only 76,875 packets were received with an unacceptable delay. In contrast with the multi-homed nodes case, the delay and loss values in that case are 16sec and 0.36% respectively.

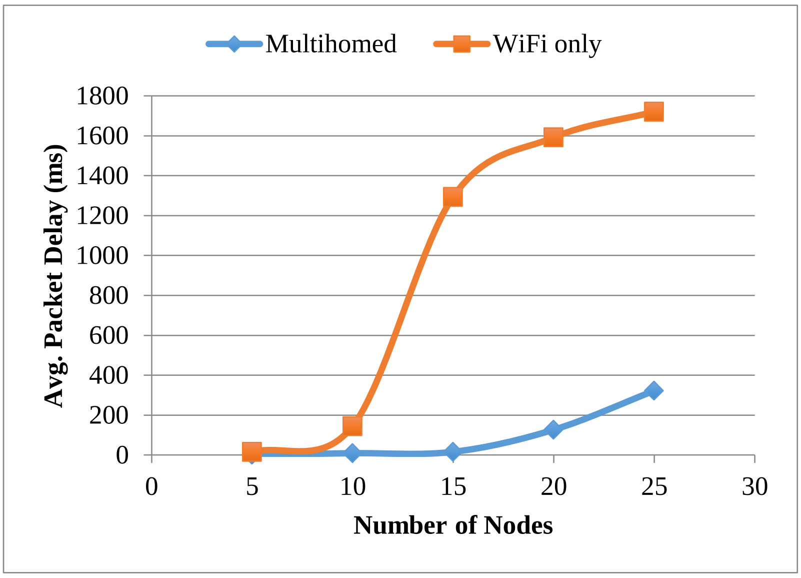


Figure 20: WiFi and multi-homed packet delay comparison

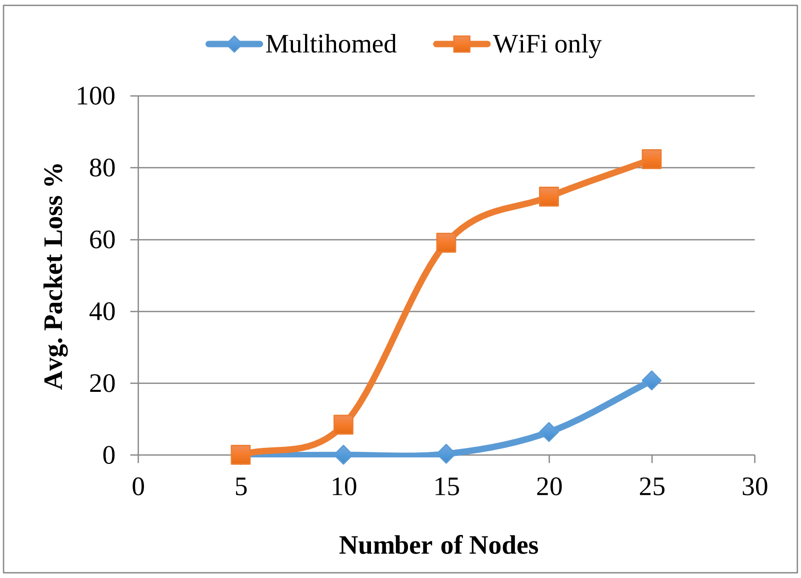


Figure 21: WiFi and multi-homed packet loss comparison

This reduction in the packet delay and packet loss is due to less processing time in the queues and less transfer time due to reduced packet collisions and retransmissions when two different interfaces are utilizing two different wireless channels.

B. LTE Interface Only

The network is simulated with LTE only interfaced nodes to compare the system performance with the multi-homed case. The number of capillary gateways is fixed at 10, LTE data rate is 2Mbps, and source rate is varied as 1,2,3,4Mbps. The delay and loss results are plotted in Figure 22 and Figure 23. The average packet delay in the multi-homed nodes network is 141ms maximum, while it exceeds 371ms if the nodes are LTE only interfaced. We notice that for a source rate 1-2Mbps, the delay difference is not as huge as it is for higher rates. The average packet loss is acceptable with LTE only as it is in multi-homed, it less than 1% in both. However, for 2Mbps source rate, the loss is above 3% in case of LTE only, which is high compared to 0.42% if the nodes are multi-homed. The loss will exceed 10% up to around 25% in both the systems if the source rate goes beyond 3Mbps, although the multi-homed continues to have less loss. The results of packet loss and packet delay in the network when the nodes utilize LTE only indicate a low QoS level compared with a multi-homing-based architecture. It is due to the fact that when the nodes are provided by two interfaces, LTE and WiFi, the LTE interface is used to serve only half of the total number of packets, while the LTE interface has to serve the total number of packets. Consequently, the packets will be delayed and some of them will be dropped, as the LTE channel is the only path can the packets go through. The queuing process in the capillary gateways also will contribute more delay, as a single interface will be used.

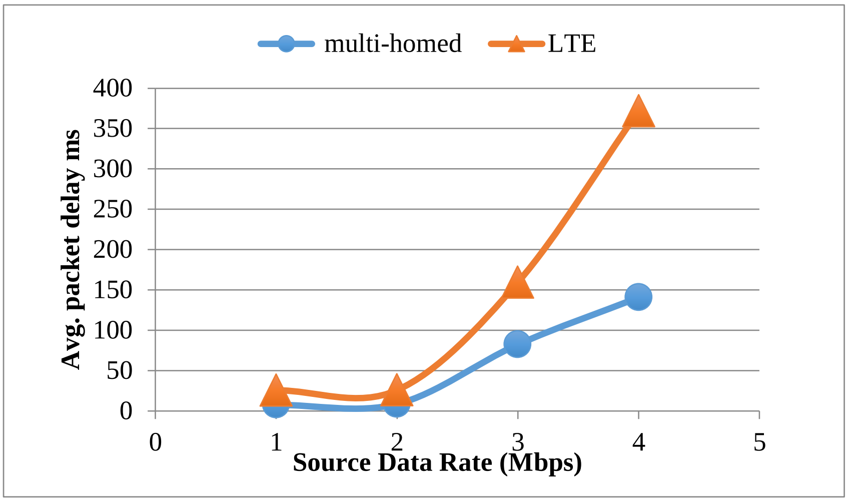


Figure 22: LTE and multi-homed packet delay comparison

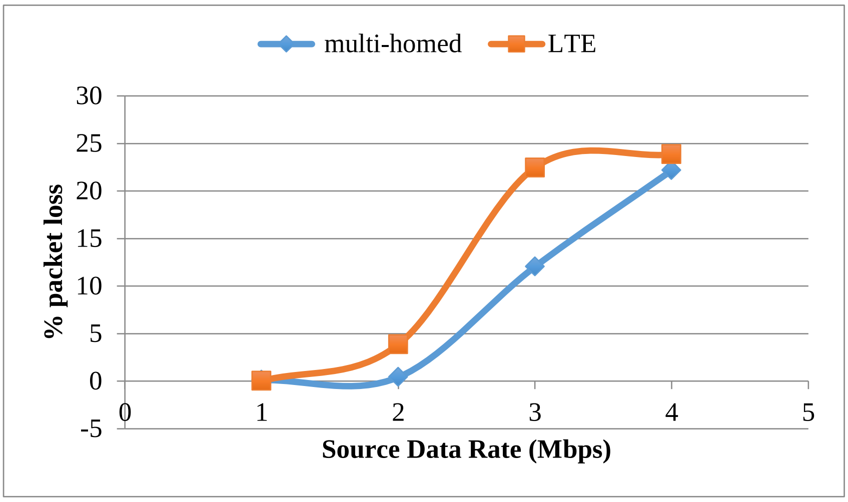


Figure 23: LTE and multi-homed packet loss comparison

C. Performance Comparison of the Proposed Architecture

To have an overview of the system in three cases, multi-homed, LTE only interface, and WiFi only interface, we compared the packet loss and packet delay in three case of a network includes 10 capillary gateways each is a source of 2Mbps. The bar chart in Figure 24 and Figure 25 illustrate that multi-homed network has the lower delay and loss limited to 9ms and 0.4%, followed by the case of LTE only, which gave a higher delay and loss up to 26ms and 4%, and the case of WiFi only shows the highest delay and loss up to 1.6sec and 72%.

To conclude, according to IEEE 802.11 MAC layer, a source has the opportunity to resend a packet for seven times, after that it will assume that the destination is unreachable and it drops the packet [30], and the delay and loss in WiFi is accumulated in the mesh backbone. For this reason the performance of our M2M capillary network scenario drops if the nodes are only WiFi interface, where only 28% of the packets will be delivered after 1.6sec delay time.

With the LTE only interface, the performance is much better than that of WiFi only, because it is single hope and no delay caused by routing. However, in our scenario, neither LTE nor WiFi can perform the recommended delay and loss for video conferencing, where the delay and loss should not exceed 150ms and 1% respectively, in order to get the desired QoS. This desired QoS is found in the multi-homed network where the delay and loss are 8.7ms and 0.4% only. In addition, the multi-homing-based architecture reduces the M2M load on the LTE network (lowering the overall usage cost) and provides better packet loss and latency at the same time.

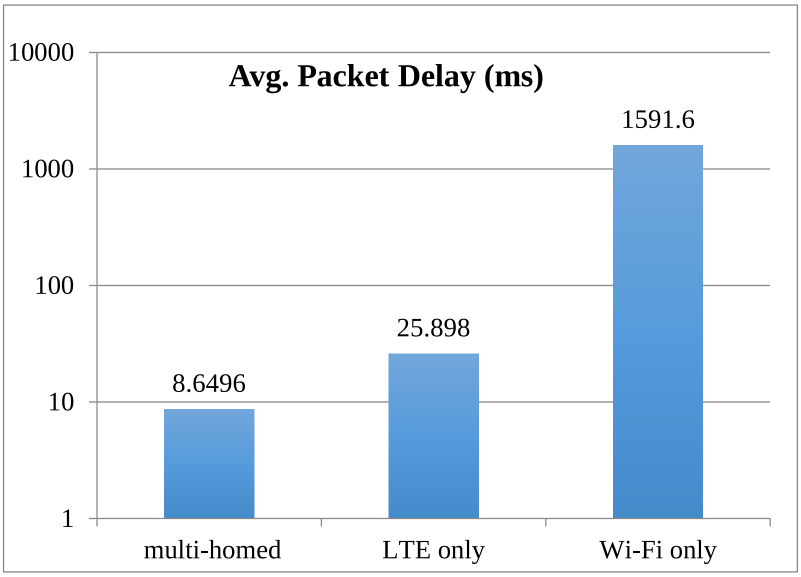


Figure 24: Multi-homed, LTE, and WiFi packet delay comparison

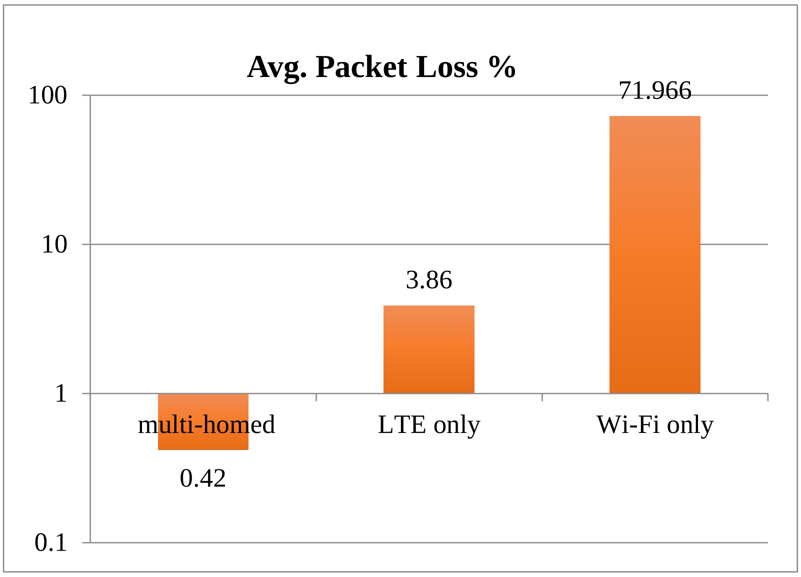


Figure 25: Multi-homed, LTE, and WiFi packet loss comparison

4.4.2 Impact of Source Rate

The behavior of the network has been simulated with increasing number of capillary gateways to observe how the average packet delay and loss are affected. The transmission nodes are capillary gateways and two types of applications are considered, namely, real-time (type A) and non-real-time (type B). It is assumed that no node contains both types of applications. The variable parameters are taken as follows:

- For Type A nodes, which are supposed to have high data rate in real time transmission, 10 capillary gateways assumed to be distributed in the transmitting area. Each gateway can be a head of 2 to 10 clustered devices whose transmission rate is 500 Kbps to 1.2 Mbps.
- For Type B nodes, which are supposed to have lower data rate, not necessarily in real time, 20 capillary gateways assumed to be distributed in

the transmitting area. Each gateway can be a head of 10 to 40 clustered devices whose transmission rate is 10 Kbps to 100Kbps.

- The source rate does not exceed the transmission rate of LTE or WiFi, assuming the service in the respective cell is efficient.
- The number of ad-Hoc routers is 10 in 100x100 m^2 area, destination servers are 2, simulation time is 100 seconds, and the total dimensions are 250x250 m^2.

The results are plotted in Figure 26 and Figure 27. In case of Type A nodes, with an average source rate 1- 5Mbps, the average packet delay ranges from 7ms to 175ms and the packet loss rate is from 0.1% to 34% approximately. In fact, the packet loss is within the acceptable limit until the source rate goes beyond 2 Mbps. At this rate t the network has to transmit 250,000 packets total, each is 1000 byte, with a total rate of 20 Mbps to two servers. Then, the delay increases significantly as the total number of packets increases, causing more packet collisions and in turn retransmissions. Consequently, more packets will be dropped increasing the loss ratio becomes to above 5% if the source rate exceeds 2Mbps. Interestingly, for the same reason, the system shows approximately the same behavior for a doubled number of nodes type B with an average source rate 100-1200 Kbps. The average packet delay starts from 6ms to 294ms and average packet loss starts from 0.01% to 15% approximately. Packet delay and packet loss raise up dramatically when the source rate is above 1Mbps. For a recommended QoS as per [50], the delay and loss are well accepted if the average source rate does not exceed 2Mbps with 10 real time applications gateways and not to exceed 1Mbps with 20 non-real time applications gateways.

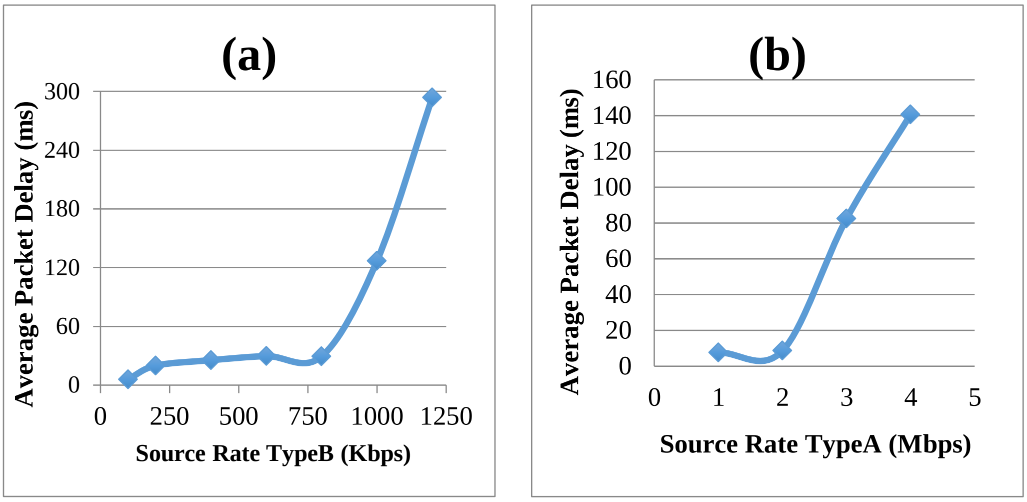


Figure 26: Average packet delay as a function of source rate

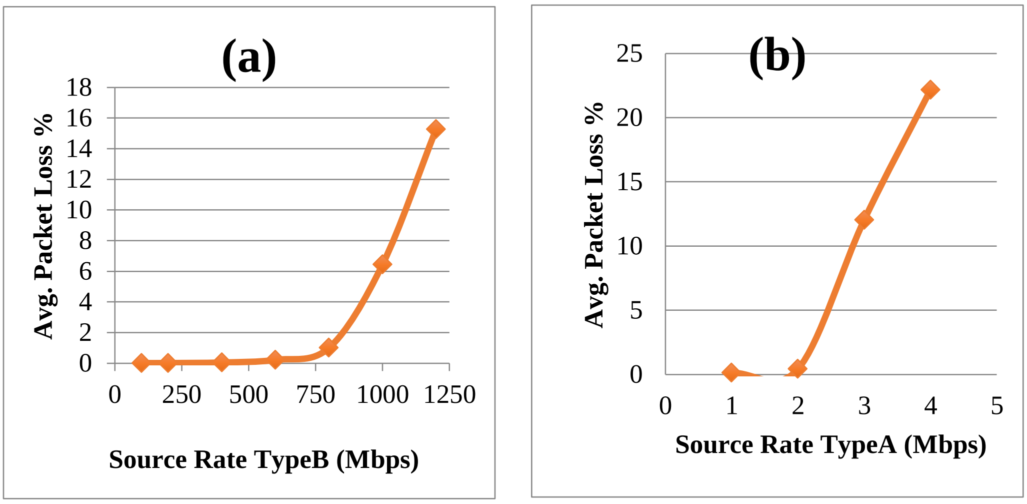
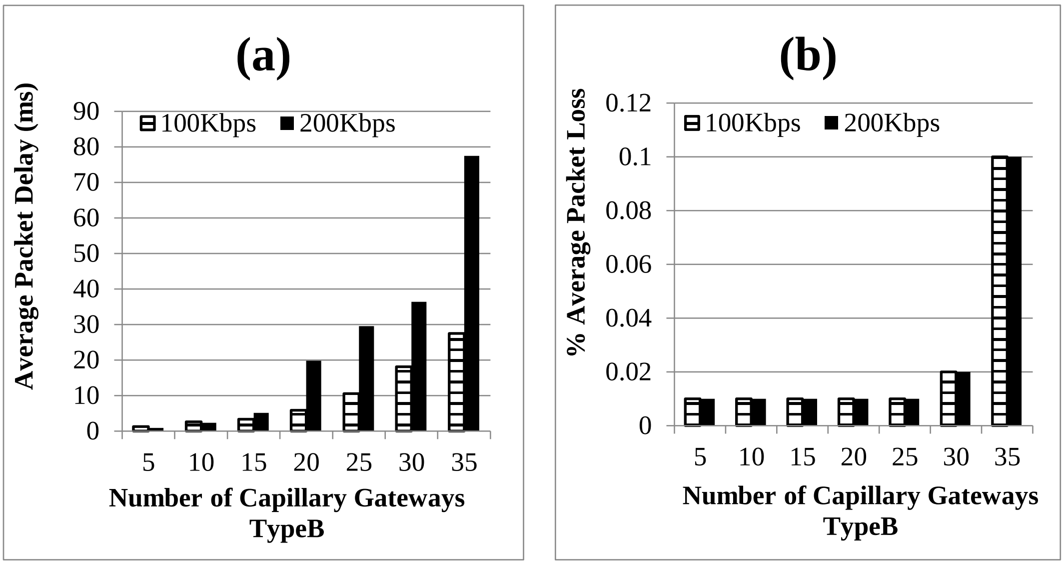


Figure 27: Average packet loss as a function of source rate

4.4.3 The Impact of Number of Nodes

Referring to Figure 19 the transmitting nodes are located in an area of 100x250m^2. Each node is multi-homed and considered to be a capillary gateway. The number of devices connected to each gateway is mentioned in the simulation model. The effect of increasing number of gateways is studied in this section. Figure 28 (a) illustrates that the average packet delay increases nonlinearly with increasing the number of gateways. The figure compares the case of two different source rates for devices

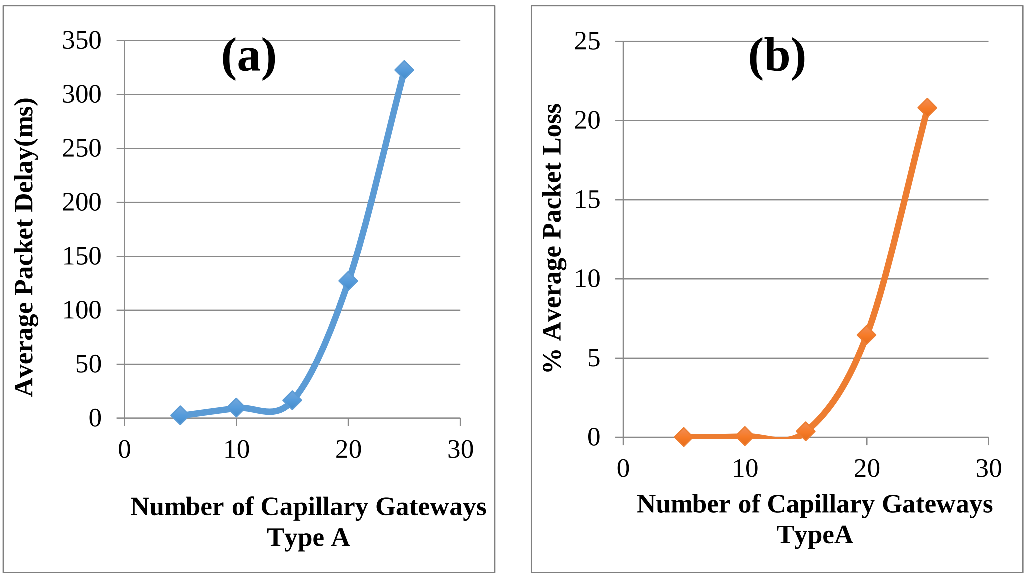
Type B. The increasing number of nodes leads to an extra load in the network, as the total number of packets to be served will noticeably increase. Since a Type B nodes has a lower source rate than Type A, the network can handle more than 35 Type B gateways without exceeding packet delay of 100ms as desired [50]. Interestingly, the average packet loss for 100 Kbps nodes is as same as for 200Kbps as in Figure 28 (b), that the extra packets will not cause more dropped packets but only extra delay.



(a) Packet delay (b) Packet loss

Figure 28: Comparison of packet delay and packet loss as a function of number of typeB nodes

In contrast, for Type A, the number of gateways can be handled in the system will be less due to the high transmission rate in real time. In Figure 29 (a),(b), we notice a dramatic increase in the average packet delay and average packet loss when the network serves more than 20 Type A capillary gateways, where the total number of packets served hits 250,000 packets in 100 seconds. This increases the chance of a packet to be delayed or in the worst case dropped if the number of packets in the queue exceeds 50. For a video conferencing case, the network cannot support more than 20 capillary gateways in order to have a recommended video QoS [50].



(a) Packet delay (b) Packet loss

Figure 29: Comparison of packet delay and packet loss as a function of number of typeA nodes

4.4.4 LTE Data Rate Impact

The target peak data rates for downlink and uplink in LTE Release 8 cat-4 are set at 100 Mbps and 50 Mbps respectively within a 20 MHz [48]. LTE-Advanced (also known as LTE Release 10) significantly enhances the existing LTE Release 8 and supports much higher peak rates, higher throughput, coverage, and lower latencies, resulting in a better user experience [53]. In the simulator, it is assumed that the LTE technology is providing 75Mbps peak rate shared fairly in the cell. The respective LTE cell is assumed to serve our M2M application devices along with H2H applications. If some fair distribution of a 75Mbps bandwidth in the cell allows each M2M capillary gateway to utilize 0.3-2Mbps data rate, then 10 capillary gateways demands a 3-20Mbps of the total LTE bandwidth assigned to M2M applications in the network. According to the promising LTE-A peak rates, up to 500Mbps uplink and 1Gbps [5] can be supported. In order to study the LTE rate impact on the network, we simulated a scenario of 10 capillary gateways each has an average source data rate of 1.2Mbps, and varied the LTE rate from 0.3 to8Mbps in order to study the case of lower provided rates than the source rate as well as higher. We vary the LTE interface rate only, while the WiFi interface rate is assumed to be 54 Mbps.

Figure 30 (a), (b) illustrates the average packet delay and average packet loss in terms of changing LTE data rates. The delay range starts by a few milliseconds and increases sharply to reach a remarkable point of 558ms, as the loss is ranged between 0.09% and 11.13%. A large delay and loss is associated with 0.3Mbps LTE rate value. After that, increasing the LTE rate causes the delay and loss to reduce and be almost constant. We notice that the critical point of the measures occurs for LTE rate 0.6Mbps after which the delay and the loss become low and constant at around 8ms and 0.1%, respectively. Referring back to the average source rate, we can easily find that 0.6Mbps is half of the average source rate, which confirms that the system QoS is accepted as long as the provided LTE rate hits half of the average source rate value. This leads to shorter interface queues, less packet delay, and in turn less chance of a packet to be dropped. The reason is that the total number of source packets is divided equally between the LTE and WiFi interfaces in the multi-homed capillary gateway, Indeed, the capillary gateway does not require an LTE rate more than half–source rate. This fact emphasizes an advantage of our network as the utilized LTE rate needs only to be half the source rate, and the extra rates can be spared to the other applications in the cell.

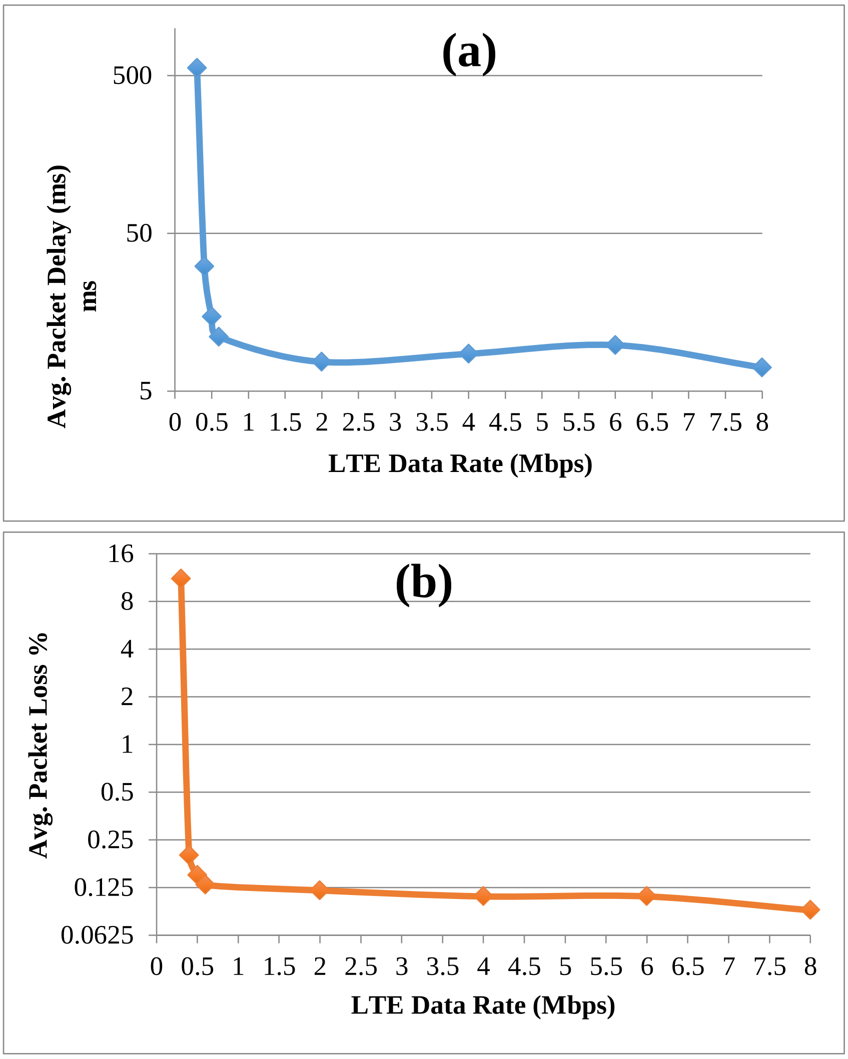
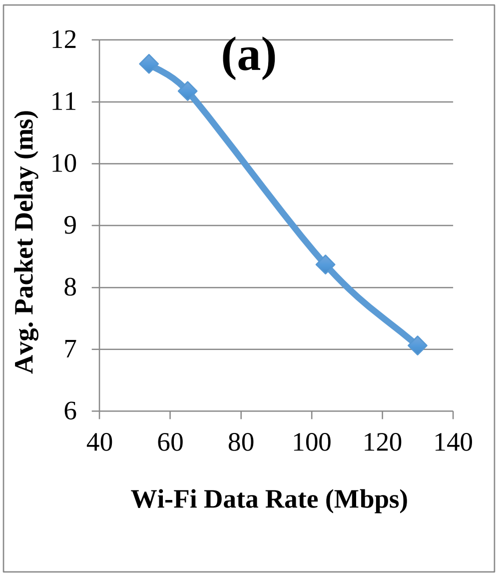


Figure 30: Packet delay and packet loss as a function of LTE rate

4.4.5 The WiFi Data Rate Impact

Networking (LAN) technology designed to provide in-building broadband coverage. Current WiFi systems typically provide indoor and outdoor coverage over a few thousand square meters based on IEEE 802.11a/g, which support a peak physical layer data rate up to 54Mbps [5]. Furthermore, using multiple antenna spatial multiplexing technology, the emerging IEEE 802.11n standard will support a peak layer up to 160Mbps with protocol 802.11n - MCS15 [54]. A scenario of 10 M2M capillary gateways each of 1Mbps source rate is simulated as multi-homed nodes with LTE data rate fixed at 5Mbps per node and WiFi data rate ranged in 54-130 Mbps per cell. The LTE data rate is chosen to be sufficiently high in order to limit the delay and loss to the WiFi interfaces only. The results are plotted in Figure 31. For the selected range of WiFi data rates, the average packet delay decreases from 12ms to 7ms, and the average packet loss is also reduced from 0.24% to 0.07%. This reduction will improve the QoS in the network and it is expected as the higher WiFi bandwidth leads to a higher rate provided for the WiFi interface in each capillary gateway. However, it is not noticed that increasing WiFi data rate causes the delay and loss to be constant after a certain point as noticed in LTE data rate case. This difference is due to multi-hop communications. The packets forwarded to the LTE base station are transmitted in a single hop, while the packets forwarded through the WiFi interface have to be routed in through the mesh network, where each hop is using the WiFi data rate in the respective router. Consequently, higher WiFi data rate continues to reduce packet collisions and retransmissions in the mesh network, which leads to reduced delay and loss. The queue of the mentioned interface is assigned to serve only half of the packets collected in the gateway, because the gateway is multi-homed. The reduced load in the queue and the efficient WiFi rate combined together minimize the delay and loss, which in turn improves the system QoS.



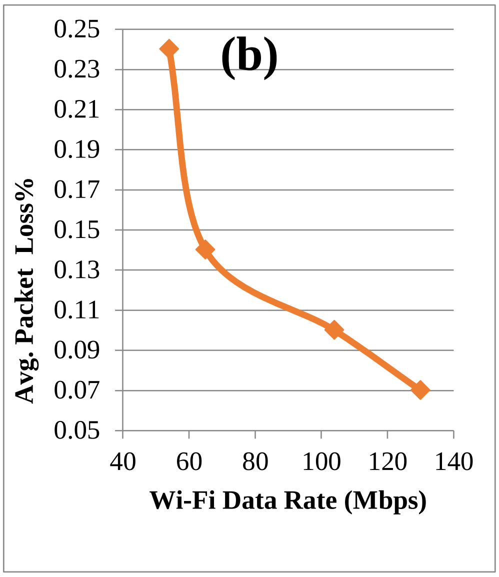


Figure 31: Packet delay and packet loss as a function of WiFi rate

4.4.6 The Effect of Number of Data Management Servers

As explained in the simulation model, the data packets sent by capillary gateways are destined to the data management servers located in an area of 50*250 m^2 shown in Figure 19. Each server is multi-homed and capable of communicating with the LTE core network and the mesh network through two separate interfaces. The multi-homed server node improves the process of data collection in the destination since the server can receive the packets from both LTE and WiFi channels. A scenario of 10 M2M capillary gateways each of 1Mbps source rate is simulated as multi-homed nodes with the LTE interface rate fixed at 5Mbps and the WiFi data rate is fixed at 54Mbps per node. The number of data management servers is varied from 1 to 8 servers. The simulation results under different number of destination servers reflect the fact that the more servers in the network, the better the achieved QoS. The results plotted in Figure 32 show a delay and loss ranges 1-14ms and 0-0.12% respectively when the number of data management servers is 1 to 8. The highest delay 14ms and loss 0.12% are noticed when the network load is sent to one server only.

When the transmitted data packets are all forwarded to one data management server, the packet delay and loss will increase due to higher number of collisions and retransmissions. The single destination is overloaded and has to coordinate with both LTE and WiFi networks. This causes an accumulated packet delay and more opportunities of packet drops as the figures illustrate. Distributing the traffic load over a number of servers reduces the packet collision each server experiences, and hence, both the packet loss and delay are improved.

Distributing the data packets in the network among more data management servers will improve the QoS by reducing the delay and loss.

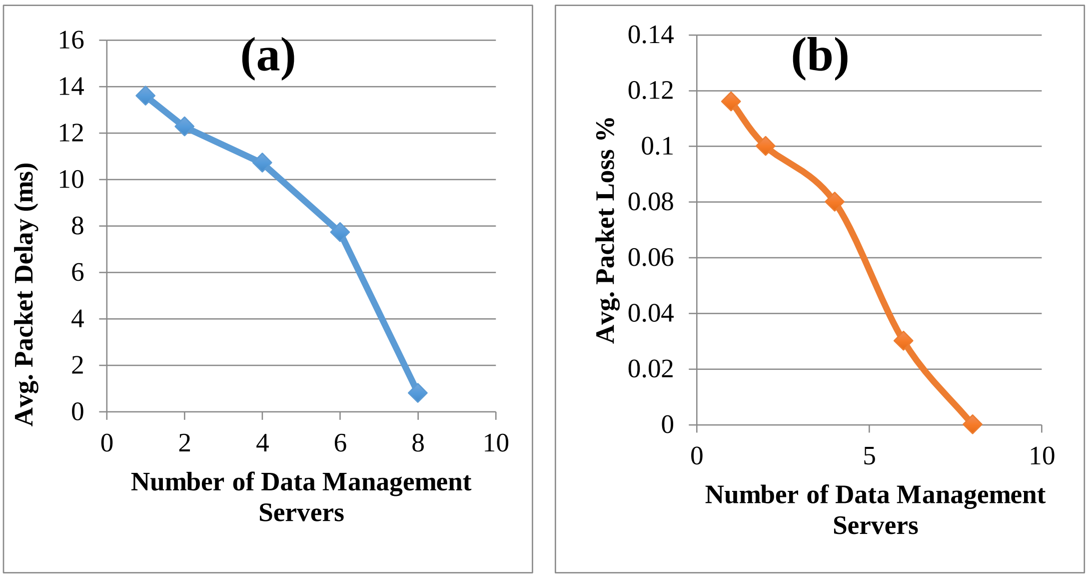


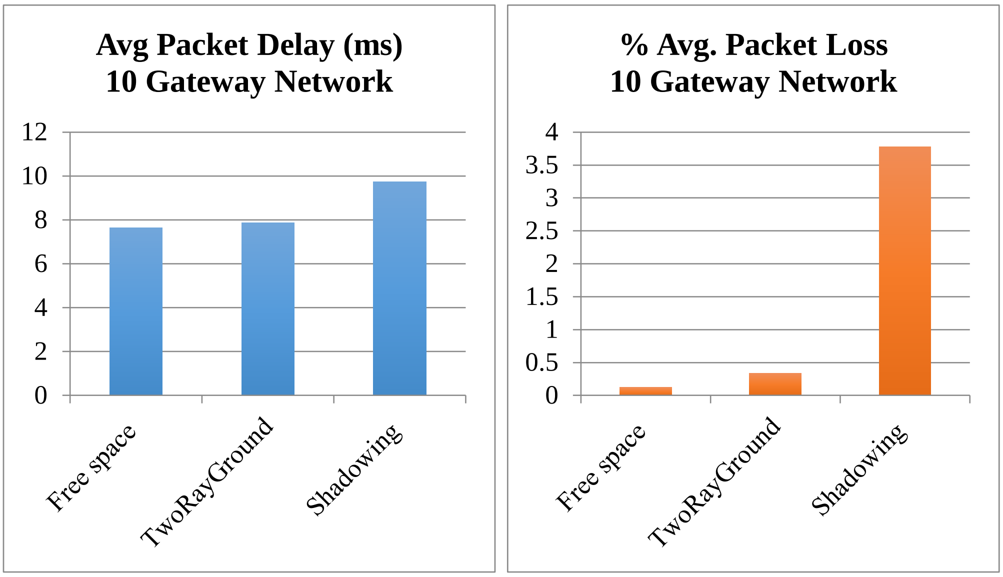
Figure 32: Packet delay and packet loss as a function of number of data management servers

4.4.7 Impact of Propagation Model

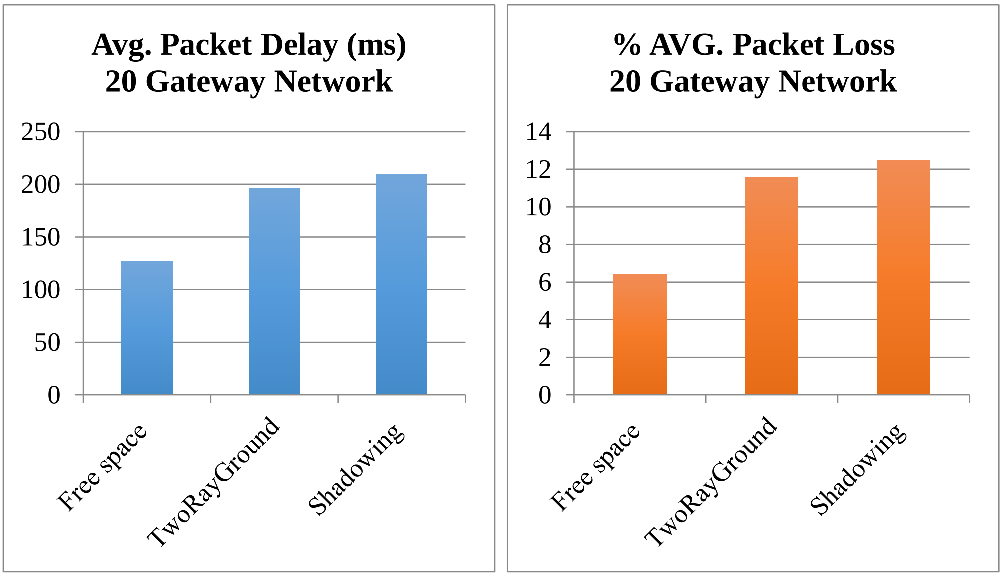
The network has been simulated under three different radio propagation model. As descripted in the system model, we simulated a network with Free Space, Two-ray Ground, and Shadowing models. Figure 33 shows the bar charts comparing the packet delay and packet loss in a network of 10 and a network of 20 capillary gateways, each with three propagation models. The source rate in this simulation is fixed at 1Mbps. In the case of 10 gateways only, because the network is not heavily loaded, there is no significant difference in the packet delay in different propagation models. It is ranged in 7.7-9.7ms. In contrast, the Two-ray Ground and Shadowing models result in a similar delay around 200ms, which is more than 1.5 times of that in Free Space. When the network is loaded by 20 gateways, the shadowing and two-ray shows a high loss around 12% compared to 6% only in Free Space. The shadowing model is known as large scale fading [41], which may affect the normal operation of IEEE 802.11 MAC and the route discovery operation [30].

As mentioned in an earlier section that IEEE 802.11 carrier sensing is performed at both the physical interface, and at the MAC sub-layer referred to as virtual carrier sensing. Due to shadowing, signal level can be below a threshold level so that it might not be detected. Hence, carrier sensing may not work properly and results in delays and losses. Similarly, variation of signal level may cause extra delays and losses due to unsuccessful RTS and CTS frame exchanging between a source and a destination. In addition, shadowing effects may cause extra delay and loss due to missing route discovery or maintenance packet lost because of wide signal variation.

Likewise, not all the transmission opportunities between eNB and capillary gateway result in a successful transmission due to signal attenuation. This argument explains also the effect of Two-ray Ground model on the system, and confirms that the system has the minimum delay and loss if the signal is considered to propagate in a Free Space model, where no attenuation affects the carrier sensing.



(a) 10 Capillary gateways



(b) 20 Capillary gateways

Figure 33: Packet delay and packet loss with differernt propagation model

4.4.8 The Effect of Number of Mesh Backbone Routers and Routing Protocol

As explained in the simulation model, half of the total number of packets is to be transmitted through WiFi and then routed in the ad-hoc mesh backbone to the management servers. The area of the mesh network, the routing protocol, and the routers density are expected to impact the QoS in the system. The packet delay and loss are observed by simulating different scenarios in the Ad-hoc part of the system. The total network area is expanded when the area covered by the mesh network expands.

4.4.8.1 Impact of Mesh Backbone Routers Density

In this simulation, the number of capillary gateways is 10; each is a source of 1 Mbps data rate. To vary the routers density (number of routers per area unit), the area of the mesh backbone is taken as 100*100, 140*140, 250*250 m^2 and the number of routers for each case is increasing as 5,10,15,20, and 25 routers using AODV or DSR protocol. The results are plotted in Figure 34. In small areas, , the packet delay and packet loss are almost constant below 20 ms and 1% respectively, in both AODV and DSR as in Fig.35 (a&b). Higher delay and loss, above 10ms, 1%, and up to 60ms, 10% respectively are observed when the number of routers is less than 15 in an area of 250*250 m^2. This means for big coverage areas, the routers density should be taken carefully because some AODV or DSR routes may be broken since some routers are outside the transmission range of others. Also the less number of routers like only 5 or 10 routers in the mentioned area will not be efficient to serve the required number of packets as the delay and loss will increase significantly when the queue length increases in each router.

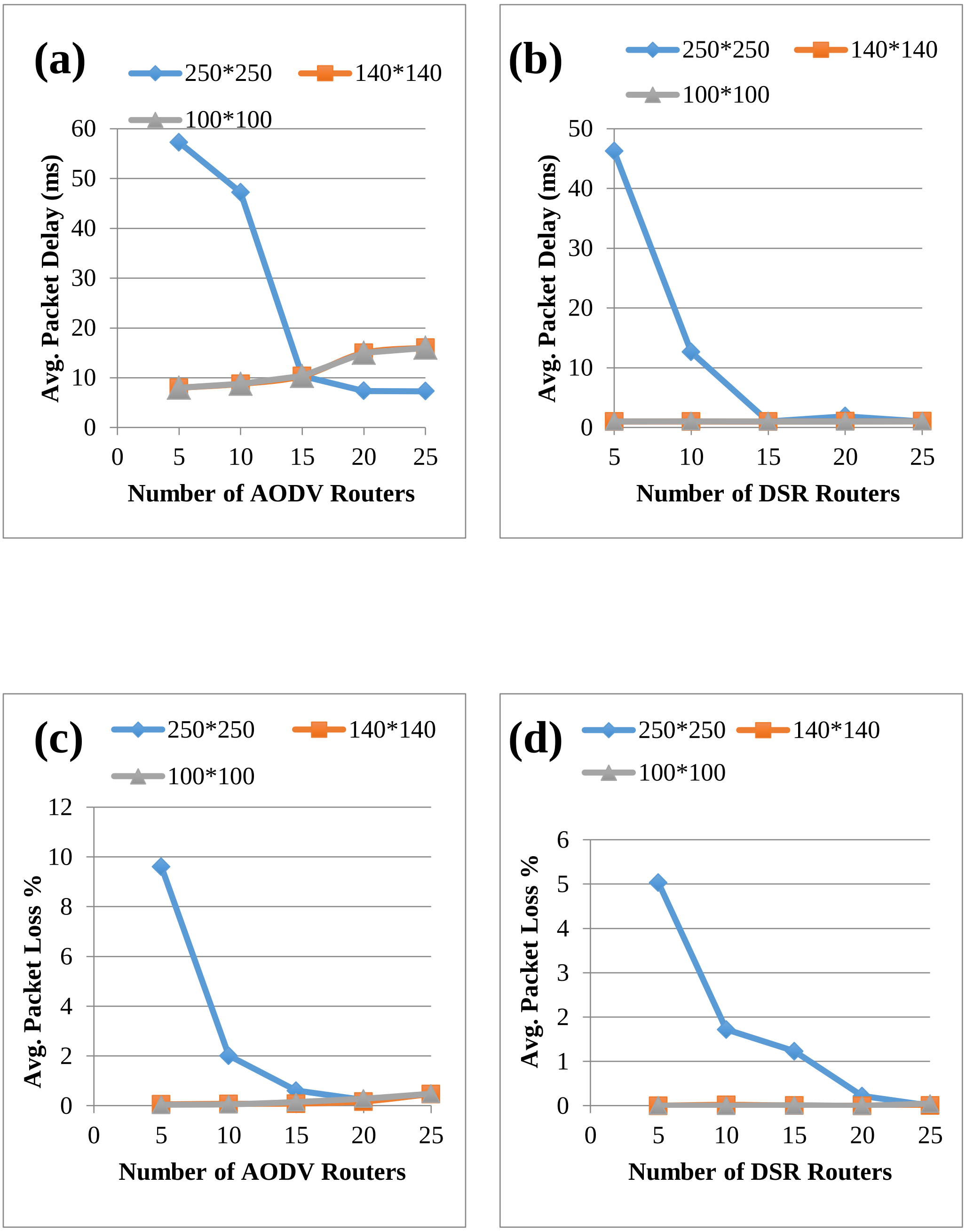


Figure 34: Packet delay and packet loss as a function of number of routers

4.4.8.2 Impact of Routing Protocol

The network is simulated under two different areas, where the dimensions are chosen to be close to the node transmission range and then greater than it. In both, the AODV is compared to DSR with a varied density from 10 -40 routers in wide areas, and 2-5 routers in smaller areas. The number of capillary gateways is 10, the source rate is 1Mbps, LTE data rate is 2Mbps per node, and WiFi data rate is 54Mbps for the entire cell.

A. Mesh Network Dimensions Close to Node Transmission Range

Figure 35 compares the impact of AODV with that of DSR on the average packet delay and average packet loss for 250*250m^2 backbone area. Both the protocols have a similar performance giving a decreasing delay and loss as the routers density increases. As explained in earlier section, DSR and AODV are both reactive protocols in which a route is established only to the required destination by a source node. This is a reason makes both protocols perform similarly in the system.

However, DSR outperforms AODV slightly for a number of routers less than 15. The delay and loss go below 20ms, 2% with 10 routers using DSR, while the AODV requires 15 routers to perform the same delay and loss. To interpret this result we recall the fact that AODV updates the route information periodically while DSR does not. This leads to a less overhead bytes in DSR than that in AODV and consequently less packet transfer time and less probability of a dropped packet. In addition, in AODV protocol, the source-initiated updated tables are used for rout discovery process; while DSR depends only on existed used routes without updates. For this reason DSR shows the better performance in terms of delay and loss.

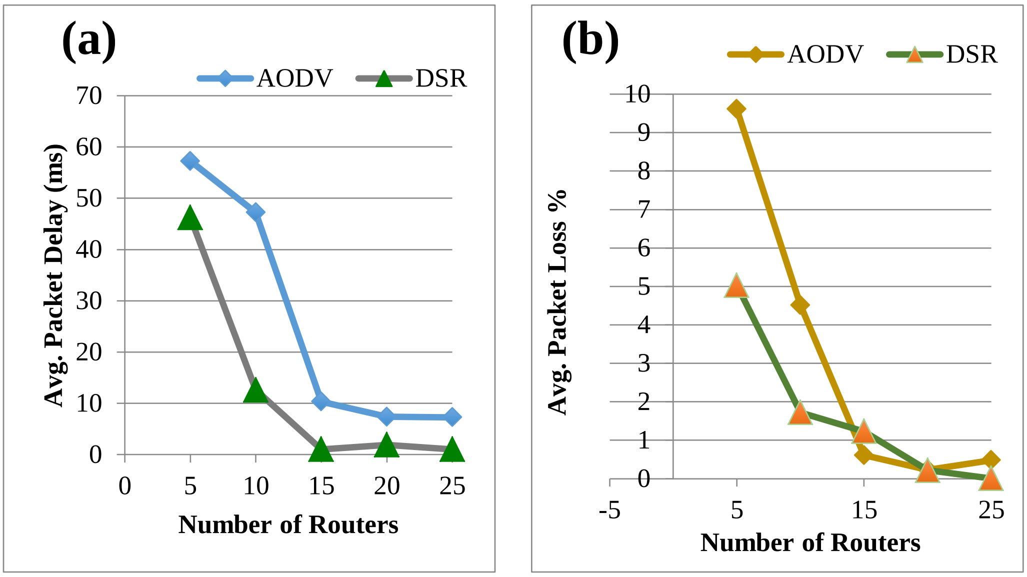


Figure 35: Packet delay and packet loss as a function of number of routers in 250*250 BKRT area

B. Mesh Backbone Dimensions Larger than the Transmission Range

In this simulation, the dimensions of the backbone mesh network are considered greater than the transmission range of the routing nodes. In an area of 400*400m2, more routers are expected to be outside the range of each other since the diagonal of the area is more than twice of the transmission range. As illustrated in Figure 36, regardless to the routing protocol, if the routers in that area are less than 30 routers, the percentage packet loss is ranged in 15-55%, which is noticeably high and makes the network unreliable even though the delay range is 10-60ms.

In reactive protocols, the route maintenance and route discovery operation, it is assumed that between two nodes there is always a stable route that can be established. The packet delay and packet loss will increase in the mentioned area as the routers density increases and the number of hops required is more. However, this can achieve higher packet delivery and consequently a very less loss.

Considering a desired loss ratio below 5%, the DSR can achieve it by 30 routers, while the AODV requires 40 routers to achieve the same, due to that AODV periodic route updates. This leads to less overhead bytes in DSR than that in AODV and consequently less packet-transfer time and less probability of a dropped packet.

In terms of packet delay, the system shows a kind of stability if the number of routers exceeds 25 routers. In that case, the delay with DSR is clearly outperforming AODV. In conclusion, the DSR protocol is deemed more effective to our proposed architecture compared with the AODV protocol.

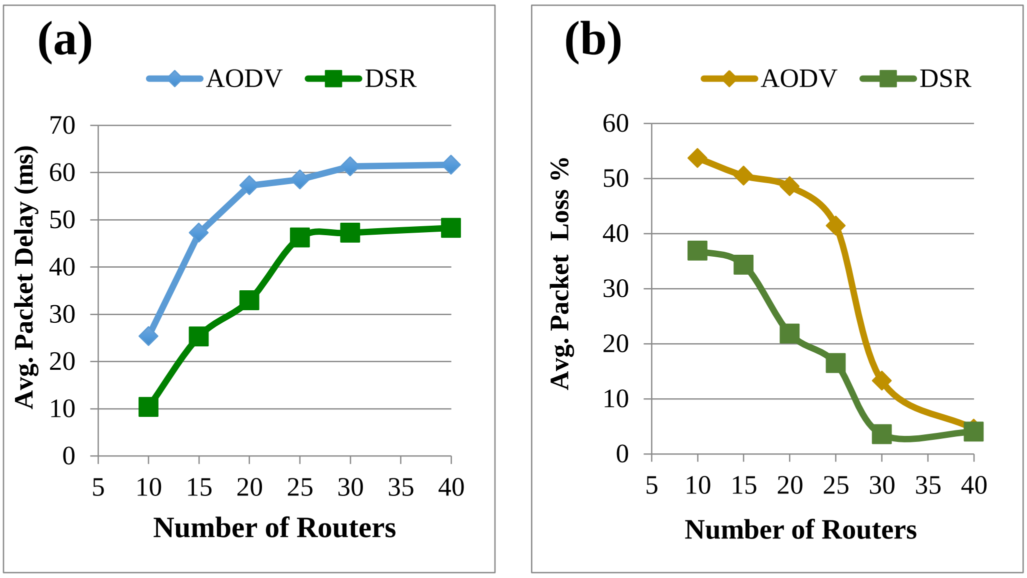


Figure 36: Packet delay and packet loss as a function of number of routers in 400*400 BKRT area

Chapter 5: Conclusion and Future Directions

M2M communications is an emerging paradigm to implement Internet-of-Things (IoT). Indeed, fast and reliable connections are required to be provided among all MTC devices in order to enable the ultimate objective of IoT in our daily life.

Capillary networks are assumed to play a potential role in solving M2M issues as they reducing the number of MTC devices communicating directly with the service provider infrastructure, such as LTE base stations or WiFi access points. In these networks, a capillary gateway forms a head of a cluster of MTC nodes. However, aggregating data traffic at capillary gateways may not satisfy the QoS level required by different M2M applications in terms of data transfer latency and packet loss. This occurs if the available bandwidth to M2M devices is not sufficient. For this issue, we propose a network architecture that combines two wireless technologies to tackle the problem of bandwidth utilization and the expected increasing load on LTE networks by M2M devices.

In this thesis, network architecture is proposed for M2M applications. In this architecture, capillary gateways, as well as, M2M data management servers are supported by 2 wireless interfaces.. One interface communicates with an LTE base station, whereas the other communicates with a WiFi access point. Furthermore, the architecture connects the WiFi access points to the data management servers through a WiFi-based mesh network backbone, while the LTE interface is connected through the LTE network. This multi-homing concept considers a parallel communication with both networks and an equal packet distribution between the two interfaces.

The performance of the proposed architecture is studied using intensive ns-2 computer simulations. Different scenarios are considered in order to investigate the impact of different network configuration parameters on the overall system performance. . In particular, the simulation aims at studying the packet delay and packet loss under different operation conditions. Moreover, the impact of the routing protocol used in the mesh backbone is demonstrated for two widely adopted ad-hoc routing protocols, namely, AODV and DSR.

Basically, the simulated system consists of multi-homed capillary gateways and the destination data management servers (also multi-homed servers). The capillary gateways are assumed to be located in one LTE micro cell as a worst-case scenario. These gateways are assumed to be under the coverage of an extended WiFi network supported by a WiFi mesh backbone, which is used to carry the WiFi traffic to the data management servers.

The performance evaluation of the proposed architecture leads to the following findings:

- The proposed architecture can significantly improve the QoS level received by M2M applications compared with a typical cellular LTE M2M network or a WiFi-based M2M network.
- Moreover, the introduced WiFi mesh backbone can extended the coverage of WiFi access points for M2M application while reducing the traffic load on the LTE network. This decreases the overall cost of running the M2M applications (compared with cellular M2M networks) and at the same time provides better QoS than using WiFi alone.

- Furthermore, by the proposed architecture,, more bandwidth-demanding M2M applications can be enabled wirelessly, like real time surveillance, as well as applications require huge number of sensing nodes, like fleet management sensor networks, which can normally cause an overload to the cellular M2M or WiFi networks. This allows the service provider to efficiently use the resources of the LTE network, while providing profitable service level agreements (SLAs) for these applications.
- Studying the impact of number of capillary gateway nodes covered by one LTE cell leads to the fact that the multi-homing technique will allow fairly good number of MTC devices to use the M2M network with satisfactory QoS level.
- Investigating the impact of capillary gateway data rate reveals that a high aggregated rates (generated by a number of real-time sources such as surveillance cameras) can be easily accommodated in the proposed architecture without a noticeable decrement in the QoS level.
- Our study shows the impact of the channel rate of LTE and WiFi systems on the performance of our proposed architecture. The study is meant to show how the performance of the proposed architecture is affected if the LTE and the mesh backbone networks are significantly utilized by other applications than M2M ones. Our findings show that our proposed architecture performs in a satisfactory manner. As redundancy of data management servers is inevitable, our simulation results show the positive impact of the number of servers on the performance of our proposed architecture. In fact, our results show that an almost arbitrary high QoS level can be reached by the service

provider with increasing the number of servers. However, this surely increases the overall cost of deployment.

- Our study also includes a comparison between two widely adopted ad-hoc routing protocols (AODV and DSR) as candidates to be used in the mesh backbone of the proposed architecture. In addition, the area of the mesh backbone network is varied along with variable number of routers to investigate the effect of routing nodes density on the system behavior. The results revealed the basis of our routing protocol selection according to the available number of routers for each area value. Generally, DSR outperforms AODV for both QoS metrics considered.
- Since the proposed architecture is to be deployed outdoors, the impact of propagation model on QoS performance is studied. Three propagation models available are compared, namely, Free Space, Two-ray Ground, and shadowing. As expected, the Shadowing model causes the longest packet delay and the highest packet loss. However, the packet delay stayed at acceptable limit with a slightly high packet loss even for the case of 20 capillary gateways each is generating 1Mbps traffic.

As a future work, we will consider the case if other devices communicating with the capillary gateway using multi-homing. We will also consider dynamic network resource allocation and its impact on the performance of our proposed architecture.

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