

Capacity estimation for IoT devices on an African mobile network

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Dissertation submitted in fulfilment of the requirements for the degree *Master of Engineering in Computer and Electronic Engineering* at the North-West University

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Master of Engineering in Computer Engineering at the Potchefstroom campus of the
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Declaration

I, Reino von Wielligh hereby declare that the dissertation entitled “Capacity estimation for IoT devices on an African mobile network” is my own original work and has not already been submitted to any other university or institution for examination.

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Abstract

Improvements in the Internet of Things (IoT) enabling technology to lead to increased potential for creating smart and safe cities for the future. While many first world countries already reap the benefits of this technology, developing countries, specifically those in Sub-Saharan Africa, still need to overcome significant barriers before experiencing the same value. Two of these barriers are a) existing network infrastructure and b) limited financial backing to implement a stand-alone IoT network. In most African cities repeated and extensive cable theft lead to the degradation of the fixed line infrastructure to such an extent that operators are reluctant to replace copper or fibre cables. The uptake of wireless technology, however, increased significantly. While cellular communication technology is prevalent in Africa, it should be noted that in most towns and cities the available technology would be a third-generation (3G) or earlier implementation. If an IoT deployment were to be considered for this environment, the currently available technology should be taken into account. In this dissertation, capacity estimation is performed for a typical town in South Africa, using the existing cellular technology as an input parameter. As an initial step towards the creation of a smart city, the case of using IoT technology for traffic light management is considered in a simulation environment. The results of the simulation verify that the current network can accommodate the load of this implementation and the maximum number of devices that can communicate using the current infrastructure is calculated.

Keywords: *African IoT, Capacity Estimation, Cellular Networks, Internet of Things, Safe City, Smart City*

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List of Acronyms

1G First-generation Cellular Technology

2G Second-generation Cellular Technology

3G Third-generation Cellular Technology

3GPP Third Generation Partnership Project

4G Fourth-generation Cellular Technology

5G Fifth-generation Cellular Technology

6G Sixth-generation Cellular Technology

A/P Asia and the Pacific

AMPS Advanced Mobile Phone Service

ANSI American National Standards Institute

ARIB Alliance of Radio Industries and Business

CDMA Code Division Multiple Access

CIR Carrier-to-Interference Ratio

ComSenTe The Centre for Converged Terahertz Communication and Sensing

EC-GSM Extended Coverage-Global System for Mobile

EC-GSM-IoT EC-GSM for IoT

EDGE Enhanced Data GSM Environment

ETACS Extended Total Access Communications System

ETSI European Telecommunication Standard Institute

EV-DO Evolution-Data Only

FDD Frequency Division Duplex

FDMA Frequency Division Multiple Access

FM Frequency Modulation

FSK Frequency Shift Keying

GPRS General Packet Radio Service

GPS Global Positioning System

GSM Global System for Mobile Communication

ICT Information and Communication Technologies

IoT Internet of Things

IP Internet Protocol

ITU International Telecommunication Union

KEI Knowledge Economic Index

KPMG Klynveld Peat Marwick Goerdeler

LAN Local Area Networks

LoRa Long-Range Technology

LoRa-WAN Long-Range Wide-Area Network

LPWAN Low-Power Wide-Area Network

LTE Long-Term Evolution

LTE-A LTE-Advanced

LTE-M LTE for Machines

M2M Machine-to-Machine

M2P Machine-to-People

MENA The Middle East and North Africa

M-IoT Mobile-IoT

NB-IoT Narrow-Band-IoT

NB-LTE Narrow-Band LTE

NMT Nordic Mobile Company

NTACS Narrowband Total Access Communications System

NTT Nippon Telephone and Telegraph Company

OTA Over The Air Update

P2P People-to-People

QoS Quality of Service

Sigfox Sigfox Wireless System

SMS Short Messaging Service

SSA Sub-Saharan Africa

TDMA Time Division Multiple Access

TTTI TomTom Traffic Index

USD United States Dollar

VAS Value Added Service

WAN Wide Area Networks

WAP Wireless Access Protocol

WCDMA Wideband Code Division Multiple Access

List of Symbols

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K	Cell Cluster Size
T	Traffic Channels
α	Path-loss Coefficient
C/I	Carrier to co-channel interference ratio
N	Traffic Channels per Cell
d/r	Co-channel reuse ratio
P	Propagation
L	Frequency dependent constant
d	Distance in m
E	Erlang
n	Total Devices
λ	Transmissions per hour
th	Hours per transmission

Chapter 1

Introduction

This chapter serves as an introduction and overview of Internet of Things (IoT) and its definition as applicable to this dissertation. The research motivation is discussed with the goals and objectives that need to be achieved in this research, and an overview of the methodology used to achieve the goals set are discussed followed by the chapter division for the remainder of the dissertation.

1.1 Introduction

The concept of IoT (Internet of Things) is one of the most pursued research topics since 2009, and it is the future of Machine-to-Machine (M2M) communication [23]. IoT devices can be categorised but are not limited to the following: Consumer Electronics, Security and Public Safety, Automotive, Utilities, Remote Maintenance, Payment and Health. In 2017, analyst firm Gartner estimated that in 2020 there would be 20.4 billion IoT devices connected (excluding smartphones, tablets, and computers) [24].

The formal International Telecommunication Union (ITU) definition of IoT is: *"A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies"* [25].

IoT technology can be deployed in various ways, but for this dissertation, an IoT deployment is defined as: *"An electronic device (sensor, mobile, pc) that is connected to the internet via any network (fibre, cellular, wireless) gathering valuable information regarding the field where the IoT device is deployed."*

For ubiquitous coverage, connectivity to various access network technologies is required. The most typical IoT applications to create safe and smart cities requires long-range networks. Common networks used for IoT devices are Long-Range Wide-Area Network (LoRa-WAN), Sigfox, Narrow-Band-IoT (NB-IoT), LTE for Machines (LTE-M) and general Global System for Mobile Communication (GSM) networks (Second-generation Cellular Technology (2G), Third-generation Cellular Technology (3G), Fourth-generation Cellular Technology (4G), depending on the IoT device application [23], [26], [27].

For IoT deployments in Africa, the network requirements cannot always be met, or when they are met, availability may not be reliable. A study regarding the readiness of IoT deployment in various parts of the world found Sub-Saharan Africa to be the least ready for IoT deployment. The study, however, didn't consider the possibility of using cellular network infrastructure to realise IoT deployments [28]. Supplementing [28], a study by [17] called *"IoT applications that work for the African continent: Innovation or adoption?"*, suggested that Africa does not adopt as various challenges in Africa are not seen in the model countries where most technology gets adopted from. A combination of these two studies led to the exploration of cellular networks as an IoT network in Africa.

The cellular growth in Sub-Saharan Africa is expected to be of the highest growing cellular networks in the next four years [29]. The prevalence of cellular technology

in Sub-Saharan Africa, therefore, makes it worth-while to consider the possibility of implementing IoT in this scenario. In this dissertation, the capacity of existing cellular infrastructure to accommodate IoT devices are investigated using a case study.

The case study chosen was yet another problem Africa faces, which is traffic congestion. A study conducted at Klynveld Peat Marwick Goerdeler (KPMG) in 2017 stated that a significant amount of time which could have been spent on more productive work gets lost as a result of traffic congestion [5].

One option to overcome this could be to upgrade road infrastructure, but this is a costly endeavour. Alternatively, congestion could be managed using an intelligent traffic system, which would be a much cheaper way to address the problem. Thus, the case study to investigate using cellular infrastructure as the primary network for IoT development is intelligent connected traffic lights for traffic management. This dissertation will conclude whether existing cellular networks in Africa would be sufficient to support IoT applications.

1.2 Research Motivation

IoT is a race for connectivity and Africa has always been adopting technology too late. With the immersive coverage of Cellular networks in Africa, it is seen as the solution to an IoT network that is needed for device implementation. Although cellular networks have been used to do remote monitoring in small use cases, this study investigates the possibility of using current cellular infrastructure as a base network for IoT deployment in Africa, solving typical African problems.

To simplify the research problem, consider the following. While many first world countries are implementing IoT on a large scale, many countries cannot even provide the basic needs of its people. The development of a country and its economy is dependent on communication technology. IoT is part of the future of communication technology; therefore, it is essential to find a way to harness this technology as a means of improv-

ing the lives of people living in Africa. Since Africa's economic climate and existing technology will significantly limit possible implementations of international solutions, the researchers from [29], decided to investigate how existing network infrastructure could be used to implement IoT in an African city. This will, therefore, not necessarily result in adopting a new network technology but rather a more intelligent use of existing technologies, thereby limiting the costs. As mentioned in Section 1.1, various networks can be used for IoT deployment in African countries, but cellular network technology is the most common communication infrastructure found in Africa [29], and it is growing at a significant rate the last four years [29].

In this dissertation, it will be estimated how many IoT devices can be connected to the current network infrastructure without compromising everyday cellular users on the same network, and whether a smart city will be possible using only existing infrastructure.

Given these restrictions, it is accepted that an African IoT and smart city may not be as sophisticated as the ones implemented in first world countries but should create a base for future IoT applications that can accommodate the necessary data that a smart city will require.

A study was done by KPMG on how many hours the average person spends in traffic each day having shocking results [5]. This study was only conducted in South Africa, but the whole of Africa has similar traffic management problems and needs a solution. For example, by implementing a network of intelligent traffic lights, it could be possible to improve the flow of traffic and reduce congestion. This type of smart city application can also be advantageous to emergency vehicles knowing that there will be less congestion on the route to an emergency scene.

By researching IoT connected smart traffic lights and how to implement it using cellular network infrastructure, an initial version of a smart city in the African context, may be realised.

1.3 Research Goals and Objectives

The primary objective of this study is to calculate the capacity of a cellular network for IoT implementations in the African context and determine the estimated capacity of IoT devices that each cellular tower can handle before the network becomes saturated. These cellular network towers must still manage daily cellular traffic as well as IoT device traffic.

The secondary objectives include:

- Identification of African IoT implementation opportunities.
- Determining an IoT scenario to investigate in a specific city.
- Estimating the current capacity of cellular towers in a specific city.
- Using IoT device parameters to estimate the number of IoT devices that can utilise cellular network capacity.

The area used as a case study in this research will be the town of Potchefstroom, and the existing coverage enabled by legacy cellular networks and alternative IoT networks will be considered to determine the highest coverage. The legacy cellular network infrastructure will briefly be compared to other known IoT network technologies implemented in first world countries in the literature study. The next step will be to determine the number of IoT devices that the cellular network can handle, and in this case, calculations are carried out to show how the cellular network in Potchefstroom will behave if each traffic light were to become an IoT device that can manage the traffic.

1.4 Research Methodology

To reach the objectives listed in Section 1.3, the following methodology will be followed:

- Gather research data regarding IoT networks.
- Research the readiness for IoT implementation across the world.
- Compare Africa as a whole to the world regarding IoT and cellular networks.
- Identify the case study for IoT deployment in Africa.
- Collect the location of cellular network broadcasting towers and plot the coverage of the network, grouped by cellular generation technology.
- Determine the geographical location of traffic lights in Potchefstroom to implement IoT as traffic management was identified as a case study.
- Determine the cellular tower capacity in Potchefstroom per cellular generation technology.
- Research the typical traffic light behaviour to determine network requirements for smart traffic lights.
- Determine the minimum and the maximum number of traffic lights that can be connected to a single cellular tower depending on generation.
- Calculate the capacity of each cellular tower.
- Tabulate results of estimated capacity per cellular tower per technology.
- Validate and Verify system model, results and findings.
- Document the findings of the research and determine whether cellular networks is a viable solution for the IoT implementation in Africa, to create an example of a safe city.

1.5 Dissertation Overview

This dissertation consists of 6 chapters and an Appendix. The remainder of this dissertation is structured as follow: Chapter 2 provides background regarding the interaction between IoT and cellular network infrastructure. Chapter 3 covers the model development, implementation and verification. In Chapter 4 the results are presented and validated before a conclusion is drawn in Chapter 5.

The Appendix consists of relevant data that was used in the estimation calculation as well as an accepted conference contribution that resulted from this study.

Chapter 2

Literature Study

In this chapter, the basics of (IoT) are discussed along with the various network technologies that can be used for implementation.

2.1 The Internet of Things

IoT has become an emerging topic not only for researchers but for the general public and with it being a relatively new concept, there are various definitions of IoT. If we were to define IoT in terms of connectedness and things separately the following definitions apply:

Connectedness: *"The interconnectedness of physical objects as a result of their ability to sense and communicate by sending and receiving messages among themselves" [28].*

Things: *"Is a diverse topic, such as computers, sensors, people, actuators, refrigerators, TVs, vehicles, cell phones, clothes, food, medicines, books and many other. These 'things' should be identified at least by one unique way for the capability of addressing and communicating with each other and verifying their identities" [30].*

IoT, in general, have different meanings, but for this dissertation, IoT is defined as in Section 1.1 as: *"An electronic device (sensor, mobile, pc) that is connected to the internet via any network (fibre, cellular, wireless) gathering valuable information regarding the field where the IoT device is deployed."*

In IoT implementations, M2M interaction takes place (currently most interconnected systems still use a human interface), but as technology evolve, each machine or device gets its own Internet Protocol (IP) address and this creates the internet of things. These devices can communicate by sending and receiving messages and information among themselves. IoT is expected to help improve the management of services and will have a positive outcome on the economy, which in turn facilitates wealth creation [28].

The number of IoT applications significantly increased over the last few years and therefore necessitates the categorisation of IoT into application domains. Some of these domains include smart cities, healthcare and public safety. [30].

According to [30], there are six main requirements for the implementation of IoT:

- The network should offer both indoor and outdoor network coverage.
- The network should support a significant number of low throughput devices.
- The network should not be sensitive to delay.
- Device cost should be low.
- Power consumption should be limited.
- The network architecture should be optimised.

Currently, various network technologies are utilised to realise IoT, but not all of them are designed for M2M applications, this includes: Long-Range Technology (LoRa), Sigfox Wireless System (Sigfox), Extended Coverage-Global System for Mobile (EC-GSM), NB-IoT, and LTE-M.

When planning for future IoT networks, a critical design aspect is energy efficient protocols and mechanisms [30]. The proposed future technology for IoT is Fifth-generation Cellular Technology (5G) networks. 5G networks are built to support M2M communications, which enables widespread coverage, mobility support, lower latency (compared to previous generation networks), longer battery life and the ability to provide an increased cellular capacity than previous network generations [31].

IoT is the heart of smart cities and will only be established when various devices from different application types can communicate with each other over an IoT network. When implementing networks for IoT, smart cities are the ultimate goal in mind to consider and not just a single use case application.

The authors of [1] estimate the IoT market will grow from 15.4 billion devices installed in 2015 to 75.4 billion in 2025 if the industry were to implement the following three instances of IoT. The authors view on this is that not having an IoT network in place makes it difficult to estimate the market growth, but an estimate of over 100 billion devices should be expected by 2025.

- Automation: By connecting various sensors, machines and actuators to a computer enable the automation process to be optimised.
- Integration: The integration of various automated machines and devices, enhances the value derived from the connected machines and devices.
- "Servitisation": When combining automation with integration a service orientated model is built and is known as servitisation. Servitisation has revenue opportunities as mobility can be sold as a service, where a machine is automated and integrated into a network, as this makes it serviceable.

2.1.1 IoT Implementations

The IoT can be implemented in various ways, but before any IoT implementations can happen the platform and components behind the technology needs to be understood.

Figure 2.1 describes the typical components of an IoT platform along with the important subsystems behind the IoT platform.

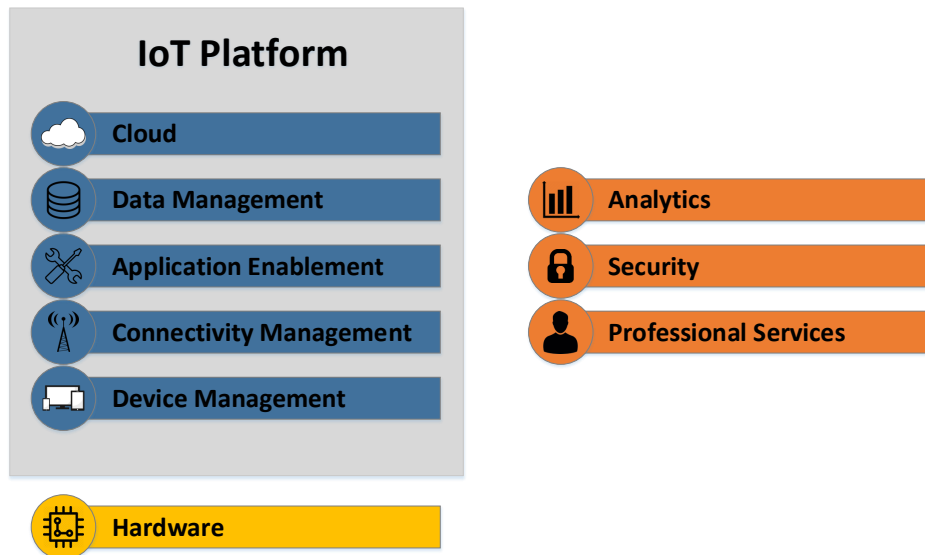


Figure 2.1: Components of an IoT Platform from IHS [1]

- Cloud/data centre: It is common practice for data to be stored and computing to be performed whether it takes place locally or in the cloud.
- Data management: The flow of data between devices and their applications should be properly managed.
- Application enablement: This helps IoT developers fast-track the implementation process, efficiently prototyping, building, integrating and managing IoT applications. Business logic and rules can be defined for the application type that leaves the developer to focus on the application differentiating aspects, which are unique to that specific application.
- Connectivity management: This may involve sim card activation, remote troubleshooting, authentication and security, flexible billing and rating, managing thresholds and alerts, and managing the physical device connection.
- Device management: Is offered by the network carriers themselves to encourage customers to move to their network. With device to the cloud services, IoT is network-centric and covers device control, diagnostics and optimisation.

IoT will have a positive impact on consumers, businesses and society. IoT is still at its early stages, and every day new services are being introduced across multiple industry sectors. While the sectors in which IoT is implemented may be quite diverse, they have the following in common [2]:

- The Internet of Things can enable the next life-changing, service across various sectors of the economy.
- Meeting the needs of customers would require a global distribution of models and global services.
- IoT presents an opportunity for new models to support mass and global deployments.
- The majority of revenue is made from value-added services, and network operators are building new capabilities for the new service areas.
- Device and application behaviour will place new demands on mobile networks.

When considering the implementation of IoT from a consumer point of view, connectivity to the cloud could enhance the quality of life in various ways, for instance, energy efficiency where smart devices can monitor and reduce utility bills or improve security within homes or across a city where smart IoT devices can remotely monitor premises.

As the demand for access to health care increases, health-related IoT applications could be used to monitor chronic diseases and age-related health conditions. Schools can utilise mobile-enabled solutions. Students would not need to carry heavy bags of books, but rather access it on a single smart device.

Different applications would have different requirements with regards to bandwidth, the extent of mobility and acceptable latency. Figure 2.2 presents a summary of the requirements of various types of applications [2].

It is clear from Figure 2.2 that the implementation of all these smart devices could result in network congestion. Smarter network management for M2M applications

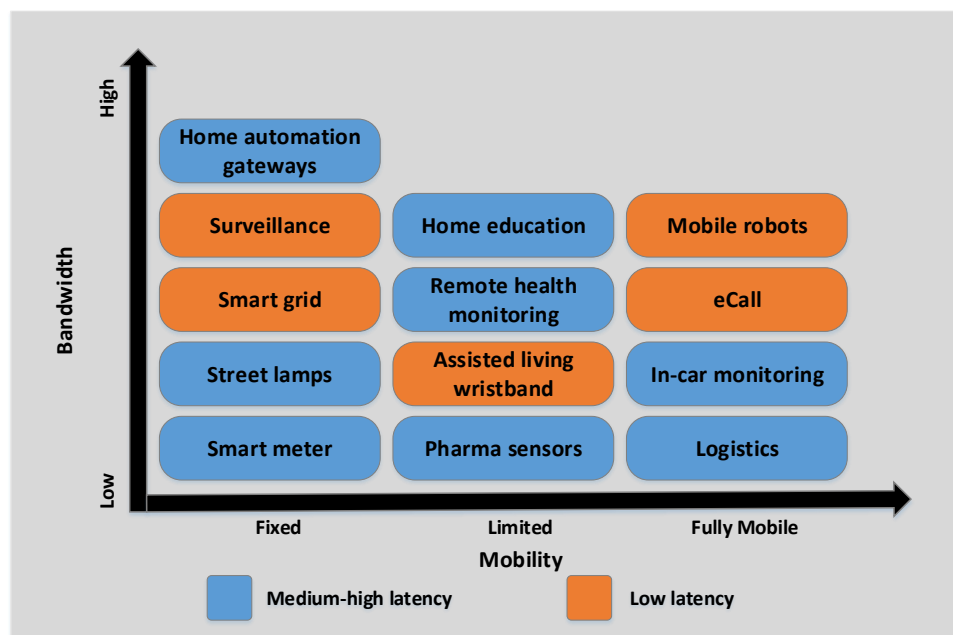


Figure 2.2: IoT application domains [2]

would need to be incorporated in future network designs. It should be noted that the case study of smartly connected traffic lights falls within the fixed category and automation/surveillance, which requires low latency and high bandwidth. This shows the first basic network requirements for the case study of this dissertation.

2.1.2 Smart Cities

The initial hype when IoT was introduced centred around creating smart cities and smart devices. According to [32], a smart city is defined as: *"A designation given to a city that incorporates Information and Communication Technologies (ICT) to enhance the quality and performance of urban services which includes energy, transportation and utilities. Smart cities are aimed to enhance the quality of life through smarter technology applications."*

Smart cities combine ICT and IoT to have optimised and efficient solutions for services and citizens in a city which enables communication both to the community and technology infrastructure simultaneously and also, addresses the issue of more efficient utilisation of space, mobility, energy, and various other services provided in larger

cities [33].

The goal of IoT devices in a smart city is to improve the lives of residents in a city by using technology to optimise services, such as traffic management services [34]. The IoT device gathers data from the smart traffic lights to show what is happening in real-time and enhance the flow of traffic. This enables a better quality of life in a city and contributes to the economic growth of the city and better time management for the drivers.

IoT is the technology that drives smart cities and can consist of various electronic devices, which includes cameras in monitoring situations, sensors in transport systems [3]. These applications rely on network communication and infrastructure. As IoT is going to be billions of devices cabling costs would be expensive; therefore the best solution is wireless communication networks. Depending on the type of IoT application in a smart city, wireless communication networks can be divided into the following categories:

- Local Area Networks (LAN) - used for short-range applications such as smart homes. The most common networks used are: Zigbee, Dash7, Wifi and Sigfox.
- Wide Area Networks (WAN) - used for distribution type applications and requires much wider coverage than LAN the most common networks include: 3G and Long-Term Evolution (LTE).
- Field Area Network, which is used to connect customers and substation. This type of application requires cellular networks.

Although some IoT have different applications, most of these devices have to communicate with each other. Therefore the wireless networks should be connected to a network which enables intelligent systems where M2M communication can then take place. Figure 2.3 shows the different application types in smart cities with the various IoT applications found within that sector [3]. In this dissertation, the traffic management case study can fall within the Smart parking lot, Transportation or Surveillance

systems as it shares usage components with all three.

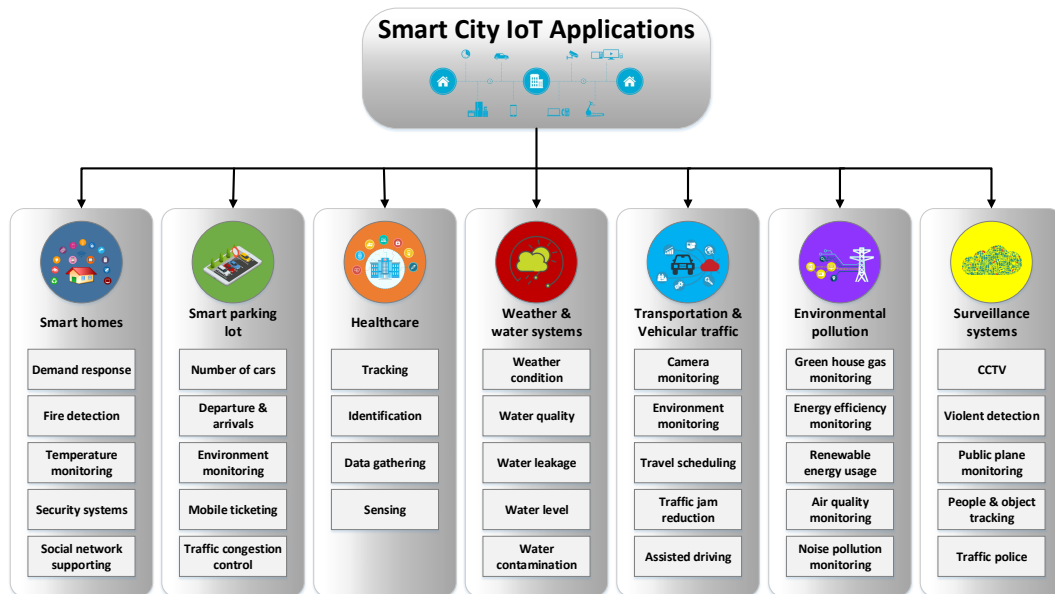


Figure 2.3: The Evolution of the Internet [3]

With IoT being the critical building block towards smart cities, the development of network communication and computer necessities have grown significantly; however, the future of IoT is dependant on the realisation of networks that can handle the billions of devices that IoT is estimated to have.

2.1.3 IoT Networks

With the full range of IoT applications in Section 2.1.2, the network market for IoT networks is still open to all players. These wireless networks can be divided into three main categories; LAN, Low-Power Wide-Area Network (LPWAN), Cellular LPWAN (NB-IoT and LTE-M) and Legacy Cellular. Although there 5G cellular networks are close to being deployed, there is not a single company that has a network configured for the billions of devices that IoT will have and in the authors view this is still what is holding back the technologies potential.

The three categories required for IoT are divided into three categories, Short-range,

medium range and long range [35].

- Short range networks - These are wireless technologies that communicate over short ranges, from a few centimetres to several meters such as WiFi, Bluetooth
- Medium range networks - Medium range networks can communicate wirelessly up to 100m, depending on the technology. Examples: LoRa, Sigfox
- Long range networks - Also known as wide-range wireless networks can communicate anywhere from several kilometres to several thousand kilometres. Examples: Cellular networks, GPS

Smart-homes/indoor smart system applications will mostly use short and medium range networks for domestic usage. Creating smart cities, however, requires medium to long range networks that are fast and reliable as it will be industrial and public usage devices.

Currently, various networks could thrive on creating smart cities with IoT devices, but they have a limit, and in this dissertation, the limit for the current cellular infrastructure for IoT usage is estimated, before looking to future networks designed explicitly for billions of IoT devices.

LoRa

LoRa is a long-range, low-power, low-bit-rate, wireless communication system, which is one of the proposed network infrastructures for IoT [12]. LoRa-WAN is designed for optimal battery lifetime, device capacity, range and cost. When compared to legacy wireless systems LoRa, does not use the Frequency Shift Keying (FSK) modulation. Instead, it uses chirp spread spectrum (CSS) modulation which also has low-power characteristics as FSK modulation, but increases the range of communication and uses less power [11].

Advantages of LoRa is its long-range communication capability. It uses a single base station that can cover entire cities. The range of LoRa, however, depends on the environment and obstructions in its given location [11]. LoRa-WAN is typically designed for sensors and application that only send small amounts of data and only very few times a day over long distances [11].

The Network Capacity of LoRa has a very high capacity or has the capability of receiving messages in high volume from various IoT devices. The use of multichannel multi-modem transceivers achieves the high capacity. This allows multiple channels to receive messages simultaneously. The main factors that affect a LoRa networks capacity are the number of concurrent channels, data rate, payload and message transmission intervals.

LoRa-WAN which is based on the same modulation technology as LoRa but with a more advanced and richer protocol, is scalable and has a high capacity, this is possible as the network can be deployed with minimal or no infrastructure, and by adding gateways to the network, the capacity can be expanded. Adding gateways maximises the capacity, and by shifting up the data rates also leads to higher network capacity. These methods can scale the network capacity by 6-8 times [11].

Table 2.1 summarises the benefits and drawbacks of the LoRa and LoRa-WAN networks for IoT applications.

Table 2.1: LoRa Benefits vs Drawbacks [11]

Benefits
- Ideal for single-building applications
- Own network managing
- Good option if you need bi-directionality
- Works well in motion
- Longer battery life compared to NB-IoT devices
Drawbacks
- Lower data rates compared to NB-IoT
- Longer latency time compared to NB-IoT
- Requires a gateway to work (can also be an advantage)

LoRa networks have the advantage of battery life over legacy cellular networks as well as NB-IoT network, the most significant disadvantage LoRa has compared to cellular and NB-IoT networks is that it has lower data rates and longer latency time, thus making real-time IoT or time-sensitive IoT applications not possible. LoRa was not considered for this study as it is still relatively new in Africa and has limited coverage.

SigFox

Sigfox is based on cellular networks, which enables devices to connect to an access point using an Ultra Narrow Band Network. Sigfox uses proprietary technology which was developed by Ludovic Le Moan and Christophe Fourtet founders of Sigfox, with little to no detailed specifications available to the public. Sigfox is operated on the 868 MHz frequency band which is divided into 400 channels, each consisting of 100 Hz [12].

Sigfox-LPWAN technology is a low powered technology which is direct competition to LoRa-WAN. It is perfect for low powered IoT applications. Sigfox works in the following way: if the network needs to transmit a message, the network wakes the device from its ultra-low powered idle mode. The message is then transmitted. The typical energy usage from a Sigfox device uses a few nanoamperes in its idle state. Because Sigfox makes use of active polling technology, it makes it a good network for data acquisition, but would not be suited for control type applications [36].

Sigfox is designed for devices that send short messages, classified in the range of 0 -6 bytes. Each end-device can send up to 140 messages per day, with a payload size of 12 bytes. The maximum data rate is 100bps, which is not a lot when compared to LTE systems. Sending small messages over Sigfox has the advantage of the network being able to handle up to millions of devices. The coverage of Sigfox networks is highly dependent on the topography of deployment where and can range anywhere from 3km - 50km [37], [12].

With the high network capacity, Sigfox can connect millions of devices. The reason for

having such a high capacity network is due to the combination of Ultra-narrow-band modulation, frequency and time diversity as well as spatial diversity due to overlapping network cells. The capacity in a Sigfox network is the same across its coverage range as when compared to most other networks where there is a decrease in capacity.

Currently, Sigfox is fully deployed in France, Spain, Portugal, Netherlands, Luxembourg and Ireland, but it is not yet deployed in Africa which is why Sigfox was not considered as a possible network in this study.

Table 2.2 summarises the benefits and drawbacks of the Sigfox network for IoT applications.

Table 2.2: SigFox Benefits vs Drawbacks [12]

Benefits
- Low power consumption
- Transmits small amounts of data slowly
- Wide coverage area
Drawbacks
- Limited use cases currently
- Communication capacity constraints, for bi-directional cases
- Mobility is difficult

Sigfox uses less power than traditional cellular networks, and can only send small packets of data at a slow rate, thus making Sigfox limited to particular use cases in IoT only, as there are communication capacity constraints when using its bi-directional functionality, communication has a better uplink to the base station, than its downlink from the base station back to the endpoint, which leads to less downlink than uplink [38]. Although this is not deployed and cannot work for the case study chosen in this dissertation, it could be a future network addition to current cellular infrastructure for data collection IoT devices that send small packets of data, like water tank levels in rural villages.

EC-GSM-IoT

EC-GSM for IoT (EC-GSM-IoT) is very similar to a legacy cellular network, 2G and 3G. It is also similar to LTE-M in that fact that it is explicitly designed to work with existing infrastructure, specifically where General Packet Radio Service (GPRS) 2G cellular networks are more prominent than LTE 4G networks. It is designed to operate with existing hardware and base stations and have minimal network implementation costs. It is good to note that EC-GSM-IoT is not yet an official Third Generation Partnership Project (3GPP) standard, but will be soon [39].

EC-GSM-IoT is backwards compatible with all older legacy cellular networks and can be introduced into existing networks as a software upgrade. Being backwards compatible also means that there is resource network sharing that can take place with dedicated resources allocated to EC-GSM-IoT. It has been specifically designed to offer a network for IoT device deployment [2].

As EC-GSM-IoT is based on GPRS, it has the designed features of a high capacity, low energy, low complexity cellular system to support IoT. The long-term plans for EC-GSM-IoT are to overlay it on top of older 2G networks instead of removing the technology from service, as the network has the opportunity to flourish in underlying areas where new networks can't be deployed due to financial constraints. EC-GSM-IoT can co-exist with conventional cellular networks and has the same security, privacy, identity confidentiality, entity authentication and data integrity benefits as legacy cellular networks [40].

Table 2.3 summarises the benefits and drawbacks of the EC-GSM-IoT networks for IoT applications.

Having all the benefits of legacy cellular networks, and the fact that the network can be implemented by a software upgrade alone, EC-GSM-IoT is a promising network for IoT applications. It uses current 2G network infrastructure as its base station, meaning there are no new network towers to be installed, which decreases the network implementation costs significantly. As this is a cellular network, coverage is extensive, and

Table 2.3: EC-GSM-IoT Benefits vs Drawbacks [13]

Benefits
Longer Battery Life compared to legacy GSM network options
Low device costs
Variable rates depending on modulation
High capacity support (50K per cell)
Improved security compared to legacy GSM
Drawbacks
Aged technology
Slower when compared to new technologies

it can support a large number of devices. This network could be a great competitor to Sigfox in Africa, as it uses GPRS as its base network and Africa mostly consists of 2G networks. It would, however, be too slow for real-time applications such as traffic monitoring discussed in this dissertation.

NB-IoT

With the development of cellular networks from the first to almost fifth generation, which is the network that is designed specifically for IoT. The necessity for IoT applications are developing and looking at 4G and LTE networks the NB-IoT network was designed for IoT applications. NB-IoT has the same characteristics as LoRa and Sigfox, also being an LPWAN network. NB-IoT is one of many Mobile-IoT (M-IoT) networks that is already standardised by the 3GPP [14].

NB-IoT networks can be deployed in the following three ways:

- Stand-alone as a dedicated carrier for IoT.
- In-band within the occupied bandwidth in wideband LTE carriers.
- Within the guard band of existing LTE carriers.

The design of NB-IoT is aimed at low-cost devices, high coverage, low power consumption and large capacity. The average capacity of an NB-IoT network is estimated

at 52 thousand devices per channel per cell. The main benefit of NB-IoT is that it can adapt to current LTE infrastructure and can even re-use hardware and share spectrum without issues. NB-IoT has low latency and can be used for authentication, security and tracking type applications. NB-IoT supports multiple carriers and having more carriers ensures that there is more IoT capacity available on the network [14].

Table 2.4 summarises the benefits and drawbacks of the NB-IoT network for IoT applications.

Table 2.4: NB-IoT Benefits vs Drawbacks [14]

Benefits
- Exceptional Coverage(Including indoors and dense Urban areas)
- Better Quality of Service compared to LoRa
- Faster response time compared to LoRa
Drawbacks
- Difficult to implement Over The Air Update (OTA) updates and file transfers
- Sending large amounts of data is difficult
- Problematic Network and tower hand-off (Suited for stationary devices)

NB-IoT networks have an advantage compared to Sigfox and LoRa networks, as it has exceptional coverage, faster transmit and receive times, it is more secure, and it is a very cost effective network as it can be incorporated within existing LTE networks and utilise unused bandwidth. However, with LTE not being deployed all over the world, it could have network problems and problematic tower hand-offs. Thus it is currently suited for stationary IoT device applications in an area where there is sufficient 4G coverage. As the 4G coverage in Africa is still minimal, it cannot be considered as a possible network for the dissertation, which leads us back to EC-GSM or Sigfox.

LTE-M

LTE-M and NB-IoT are very similar networks, and it is thus critical to understand the difference between these two networks. Although both of these networks are designed for the IoT environment LTE-M has better latency and speed when compared to NB-

IoT. This makes LTE-M the only network option for mission-critical and real-time IoT applications [16].

LTE-M is a machine focused variant of the 3GPP LTE standard, which is designed for high-coverage, low-cost and low-power consumption for IoT devices. LTE-M coverage is significantly better when compared to LTE or legacy cellular networks and even meets the -164dBm threshold minimum for 5G networks [41]. Regarding the capacity of LTE-M networks, there is still optimisation that needs to be made, as LTE was designed for few simultaneous users with very high data rates, whereas IoT traffic requires many users each with low data rates [15].

All major mobile equipment and chipsets support LTE-M. Thus LTE-M can co-exist with 2G, 3G and 4G cellular networks, and has the same security features as offered by legacy cellular networks [42].

Currently, LTE-M networks are only being deployed in North America, Canada, Latin America, Europe and parts of Asia, with no African deployment yet [43].

Table 2.5 summarises the benefits and drawbacks of LTE-M networks for IoT applications.

Table 2.5: LTE-M Benefits vs Drawbacks [15]

Benefits
- LTE-M has higher data rates compared to NB-IoT
- LTE-M benefits from reduced complexity
Drawbacks
- Slow or no deployment rate
- Legacy licensing costs are involved
- Power efficiency is good but not great

When compared to any of the LPWAN technologies, LTE-M has the highest bandwidth, and with its fast latency, LTE-M is the ideal IoT network for fixed and mobile application types that are mission critical and real-time. As LTE-M can co-exist with 2G, 3G and 4G cellular networks and use most of the same infrastructure equipment, it could be the most economical network to enable a full-scale roll-out of IoT in Africa

as some of the decommissioned towers hardware can be utilised for LTE-M. Although this could be a possible network for the future of Africa, the problem persists that 4G coverage in Africa is poor, thus using current cellular infrastructure for the start of IoT would be the best viable option, not just for availability but also cost wise.

IoT Networks Summary

LoRa, Sigfox, EC-GSM-IoT (Cellular), NB-IoT and LTE-M are all capable networks that can be used in the implementation of IoT devices. It is noted from the brief description of each network with its drawbacks and benefits that although all these networks can support millions of devices, LoRa cannot support real-time as it has lower latency and lower data rate support than the other networks. NB-IoT still has implementation issues and can only be deployed in IoT applications that is stationary as there are hand-off issues. Table 2.6 shows each technology with the frequency band it operates in, the data rate, range, power usage, capacity and cost.

Before deploying IoT, it is necessary to determine, which networks are available locally and which hardware is supported for those networks, as some IoT applications require higher data rates than other or have different power requirements. Another critical factor to consider is network coverage and device power consumption [16], and of all these networks the lowest power consumption is LoRa and Sigfox, both not fully deployed and available throughout Africa.

Many network operators are studying IoT requirements and investigating the threats these new technologies bring. Nokia's view is that EC-GSM, LTE-M and NB-IoT are superior cellular network solutions that can satisfy the connectivity demands and profiles of all the different types of IoT applications. It is easy to implement IoT on current infrastructure since cellular IoT provides easy software upgrades to the current network infrastructure to optimise devices battery life, coverage and cost [15] and as the author, I wholeheartedly agree to this for the future of IoT in Africa, but for now, 2G and 3G cellular networks must do.

Table 2.6: Comparison of possible IoT Networks [11], [4]

Technology	LoRa-WAN	Sigfox	EC-GSM	NB-IoT	LTE-M
Freq bands	subGhz	subGhz	Cellular bands	Cellular bands	Cellular bands
Data rate	<50 kbps	<1kbps	10Mbps	0.1-1Mbps	0.2-1Mbps
Range	1-5 Km	n Km's	n Km's	n Km's	n Km's
Max num msgs/day	Unlimited	Unlimited	Unlimited	140	Unlimited
Power Usage	Low	Low	High	Medium-High	Medium
Interference Immunity	Very High	Low	Medium	Low	Medium
Coexistence	Yes	Yes	Yes	No	Yes
Security	Yes	Yes	Yes	No	Yes
Mobility/ Localization	Yes	Yes	Yes	Yes	Yes
Cost	Medium	Medium	High	High	High

Table 2.7 shows how Cellular IoT directly compare to LoRa and Sigfox as they could be the best candidates for other IoT applications in Africa.

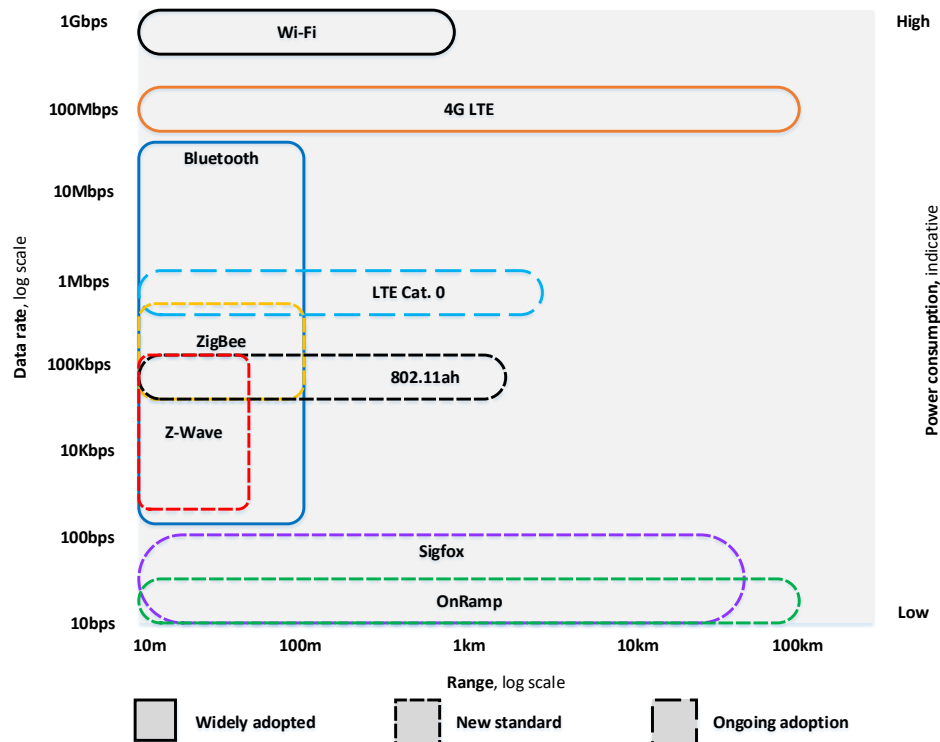


Figure 2.4: IoT networks speed vs. coverage vs power consumption [4]

Figure 2.4 shows each technology in the IoT network. The three main areas when choosing an IoT network is the range, data rate and power consumption. Figure 2.4, indicates that Sigfox have the lowest power consumption and most extensive range, but does not have a high enough data rate for monitoring and real-time applications. Thus the best current network for IoT if the application has an unlimited power supply would be 4G LTE. Thus any cellular network EC-GSM-IoT(2G/3G), LTE(4G) or LTE-M would be sufficient networks for real-time IoT applications, as most have very high data rates and large range but they do consume much power and would require a constant supply.

Table 2.7: Comparison of Cellular networks vs. Sigfox/LoRa-WAN for IoT Applications [16]

	Cellular M2M Network	Sigfox/LoRa-WAN Network
Ideal use Case	GPS telematic trackers	Automatic meter reading
	Smart meters	GPS tracking devices (in a defined area)
	Connected cars	
Positives	Ubiquitous network coverage	Power efficient Inexpensive chip sets Low certification costs
Considerations	Recurring cost Expensive chip sets Shorter battery life Expensive certification	Low data throughput Networks do not exist everywhere QoS not guaranteed in unlicensed spectrum Current provisioning and key management schemes make large scale manufacturing difficult.

2.1.4 IoT Readiness

The development of a country and its economy depends on communication and the way people interact and connect with each other [31]. IoT is a fast emerging shift in networking and communication paradigms for both people and machines. The economic position of a country limits the ability of the country to embrace the possibilities offered by that country. This is the case found in this study as Africa can barely supply basic needs, but to move forward, they need to embrace IoT. Various studies were done to assess the readiness of Sub-Saharan African countries to innovate with IoT or to join the rest of the world on the IoT evolution through technology adoption [31], [44], [28]. In my view, Africa should innovate with IoT, although it might not be the latest and greatest technology it would be specific to African needs.

In Table 2.8, a summary of the IoT readiness study can be seen. Africa houses 35 of the 45 poorest countries in the world, and most of these countries struggle to provide basic needs to people especially in Sub-Saharan Africa (SSA) [17]. This reflects on the results of this study as SSA had the lowest score in all fields.

Based on the economies of Sub-Saharan African countries (SSA), The Middle East and North Africa (MENA), Asia and the Pacific (A/P), Americas and Europe, an IoT index was used to gauge the preparedness of countries to implement IoT. The indices that were used to create the IoT readiness index included: Network Readiness, ICT Development, Global Innovation, Global Competitive, and Knowledge Economic Index (KEI).

From Table 2.8, SSA scored the lowest in all fields, showing that it is the least ready to implement IoT.

In 2013 there were no known documented IoT deployments in Africa as a result of the lack of infrastructure and cost. Fixed broadband subscriptions costs are higher than 30% of the monthly incomes in Africa, proving that it would be unsustainable for African economies. However, mobile broadband costs are less than half of fixed broadband costs which shows the possible solution to fixed broadband and the future

Table 2.8: Worldwide IoT Readiness Study Summary [17]

Index Type	SSA	MENA	A/P	Americas	Europe
Network Ready	3.80	4.40	4.10	4.40	5.78
Developed Countries	3.80	5.72	7.23	6.40	8.41
Innovative Countries	3.23	—	5.08	4.20	6.0
Competitive Economies	5.77	6.65	7.40	6.55	7.71
Knowledge Driven	3.67	5.87	7.73	6.74	9.02

of African IoT. Internet connectivity in Africa is much more accessible from mobile phones and rather than building landline infrastructure and then moving to mobile, Africa is jumping straight to mobile [17]. IoT has the potential to solve underlying problems in Africa such as environmental, climate change, agriculture, health and security problems [44], [45], [30].

2.1.5 IoT in Africa

In Section 2.1.4, it was concluded that SSA countries was the least ready to implement IoT, but cellular networks were not considered in the study. In Section 2.1.3, a summary of the cellular connections in each continent will be discussed. It was noticed that from 2014 until the prediction of 2023, 2G and 3G networks will still be widely used compared to 4G and the new 5G cellular networks. Africa as a whole does not have a lot of IoT projects on its own, but certain African countries took the initiative in deploying minimalistic IoT applications. These countries include; Tanzania, South Africa, Kenya, Nigeria, Egypt and Namibia [46].

IoT applications are possible in Africa, which could lead to economic growth in Africa

[47]. However, before IoT applications can be implemented some IoT adoption challenges still need to be faced. With Africa having mostly all developing countries they stand the change to benefit the most from IoT as it will change people lives, improving processes, services, channel deliveries and many other daily tasks. With the implementation of IoT having such positive anticipations, there are some challenges involved. These challenges include governance, policy frameworks, data security, privacy, business models and various ethical issues. The main concern is technology challenges which include: network access, infrastructure, interoperability and standards. The African infrastructure needs to be expanded as the current infrastructure only supports 10% penetration and IoT depend entirely on robust infrastructure and uninterrupted connection to devices. With some countries in Africa trying to implementing some form of IoT connections, they are choosing cellular networks because of its extensive coverage, and it has the best potential for IoT deployment in Africa [46].

African IoT Case Study

Traffic management has become a serious concern in developing countries, a case study done in 2017 in South Africa on "The Economics of rush hour traffic", showed some concerns about the amount of time spent in traffic daily and how it can be improved.

The data used was from the TomTom Traffic Index (TTTI) of 2017, and South Africa was the only African country included in the index. Figure 2.5, shows the increase of time spent in traffic the last seven years from 2009 to 2017 [5], [6].

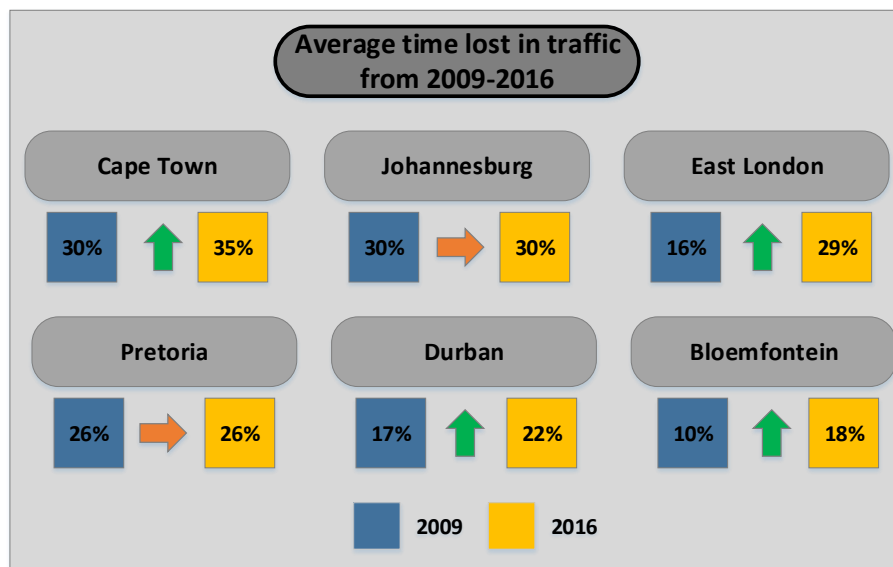


Figure 2.5: Time lost in Traffic 2009-2016 [5], [6]

Johannesburg is the most populous city in South Africa and has been perceived as the most congested city, but since 2012 that has changed to Cape Town being the most traffic congested city. Table 2.9 shows a summary of the 3 top congested cities in South Africa and the time spent daily and yearly in traffic [5].

Table 2.9: Average time lost in traffic in South Africa [5]

City	Cape Town	Johannesburg	East London
Minutes lost per day	42	37	32
Hours lost per year	163	141	121

With this information known it is quite alarming to notice the number of hours that vehicle drivers waste in traffic. This does not only have a negative effect personally but on the economic growth of a city. As all cities in Africa is developing cities with growing economies; this problem of traffic congestion is common in Africa as a whole. Some possible solutions to the congestions include the following [5]:

- Road Constructions/Improvements
- Bus Lanes/systems
- Carpooling
- Parking
- Congestion Charges
- Flexible working hours
- Toll roads
- Traffic management systems

Of all these solutions the easiest to implement is carpooling and flexible working hours. However, the cheapest solution alternatively than building new infrastructure is traffic management. Smart traffic management systems could solve most of the congestion using smart traffic lights and sensors.

2.2 Cellular Networks

Cellular networks have evolved since its first discovery in 1980 with the first generation mobile system (Analog). Since then, the second-generation (digital) with GSM, Value Added Service (VAS), GPRS and Enhanced Data GSM Environment (EDGE) was developed. An international standardised 3G cellular system followed 2G. A fourth-generation network was developed using IP to have a common platform for all developed technologies [48], [49]. 4G is the current fastest deployed network in the world and is less expensive and can transfer data much faster than previous generation networks. Considering how technology has evolved over the past years, the fifth generation networks will be ready and implemented by 2020 [23]. 5G networks are specially designed for IoT and M2M communication. This means having low latency standards and faster data transfers than 4G networks [50], [51]. As the cellular network evolved

from sending a text to making calls, the internet joined the evolution and now moving into the world of IoT. This section will give an overview of where cellular networks began and how it evolved to today.

2.2.1 Cellular Network Standards

There are many various standards for cellular networks, with each standard having their reason for their differences. The most common network standard used in cellular technology is the ITU and produces standards covering all the fields telecommunication. Some other standards used across the world are European Telecommunication Standard Institute (ETSI), Alliance of Radio Industries and Business (ARIB) and American National Standards Institute (ANSI) [52]. All these standards adhere to the 3GPP, which is in the control of network releases and each time there is a major network change the 3GPP releases a new G (Generation) This naming convention with the number refers to the releases in chronological order, 1G, 2G, 3G, 4G and 5G.

Although the networks have different releases, they are mostly backwards compatible, and devices from 3G networks can communicate with devices from 2G networks. In this study the basic principle of the 3GPP was used, which is that 4G networks are better than 3G, 3G networks are better than 2G, and 2G networks are better than 1G networks regardless of which standards were used in the design and implementation of these networks. These basic differences of a 2G, 3G and 4G network were used as a reference point for this dissertation.

2.2.2 Cellular Networks in Africa

Cellular networks have passed various milestones in the last two decades, and it is difficult to know how cellular networks would impact our society in the future. The most noticeable change to cellular networks is 5G and IoT technology. This new way of cellular communication will impact consumer services and industries embarking in

the 4th industrial revolution, which is focused on digital transformation [7], [8].

Cellular IoT is growing at a fast rate, and 2018 showed high growth in mobile traffic, but as 5G and IoT enter the market of cellular technology the growth of cellular users will drastically increase in the coming years. Looking at the mobile subscription numbers by region for 2014, it is shown in Figure 2.6, that The Middle East and Africa had the lowest LTE mobile subscriptions in 2014, and still mostly relied on 2G and 3G cellular networks and from an African cellular user perspective this is valid results [7], [8].

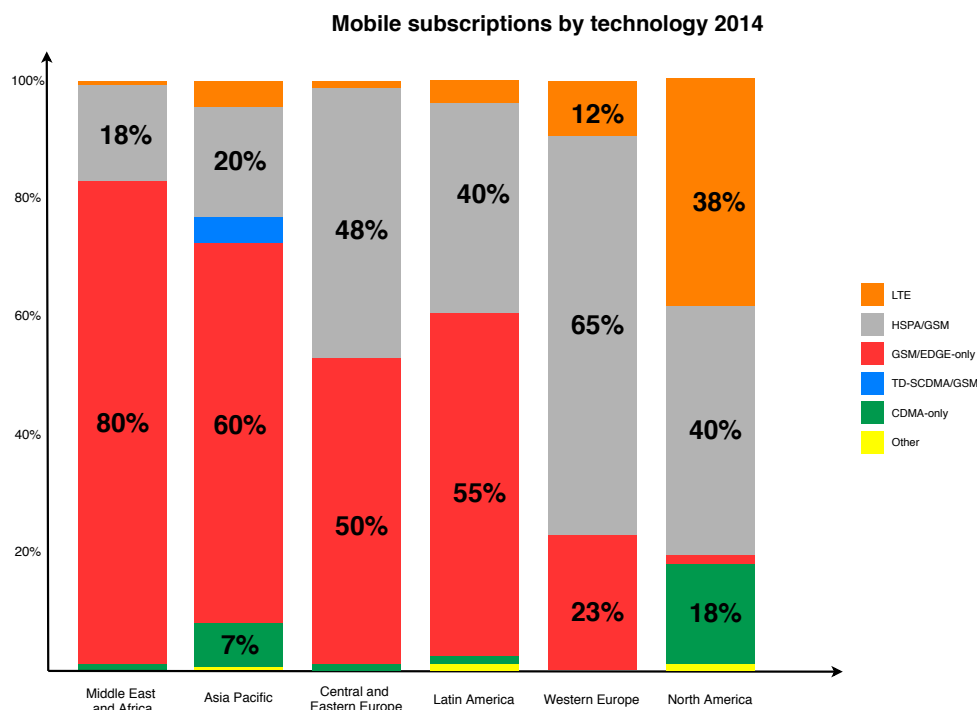


Figure 2.6: Mobile Subscriptions 2014 [7]

Looking at mobile subscription figures from 2017, in Figure 2.7, 5G networks has not been implemented yet, 4G cellular connections are used by the vast majority of mobile users in 2017 followed by 3G and 2G connections. Looking at the cellular connections in The Middle East and Africa solely, 50% of mobile subscription is through 2G (GSM/EDGE) technology followed by close to 40% using 3G (WCDMA/HSPA) technology. 4G technology in The Middle East and Africa account for 8% of mobile subscriptions. This regions data consist of 70 countries and by the end of 2017 nearly

20% of mobile subscriptions were for LTE in The Middle East and North Africa, and Sub-Saharan Africa's LTE subscriptions accounted for only 5% of its cellular connections.

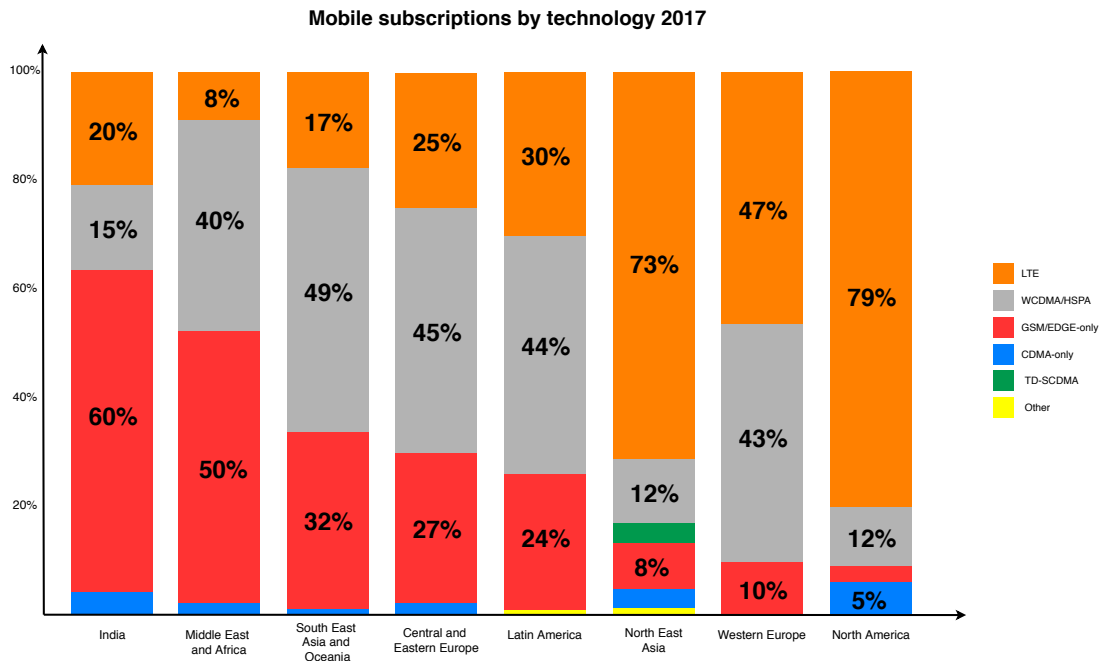


Figure 2.7: Mobile Subscriptions 2017 [8]

Ericsson Mobility Report of 2018 also predicted mobile subscriptions for 2023, seen in Figure 2.8. It is clear that although 5G networks are going to be implemented by 2023, the vast majority of mobile users will be using 4G cellular connections except for the Middle East and Africa regions as well as South East Asia and Oceania, which will still have the majority of 3G cellular connections. Considering the 2G cellular network, it will mostly be used in India, Middle East and Africa as well as Latin America.

Comparing the results from 2014 and 2017 and the prediction for cellular networks in 2023, it is clear that 5G would have been well implemented in 3 regions across the world, but considering cellular network subscriptions in Africa, 47% would be 3G (WCDMA/HSPA) technology, <40% 4G (LTE) technology and <10% 2G (GSM/EDGE) technology.

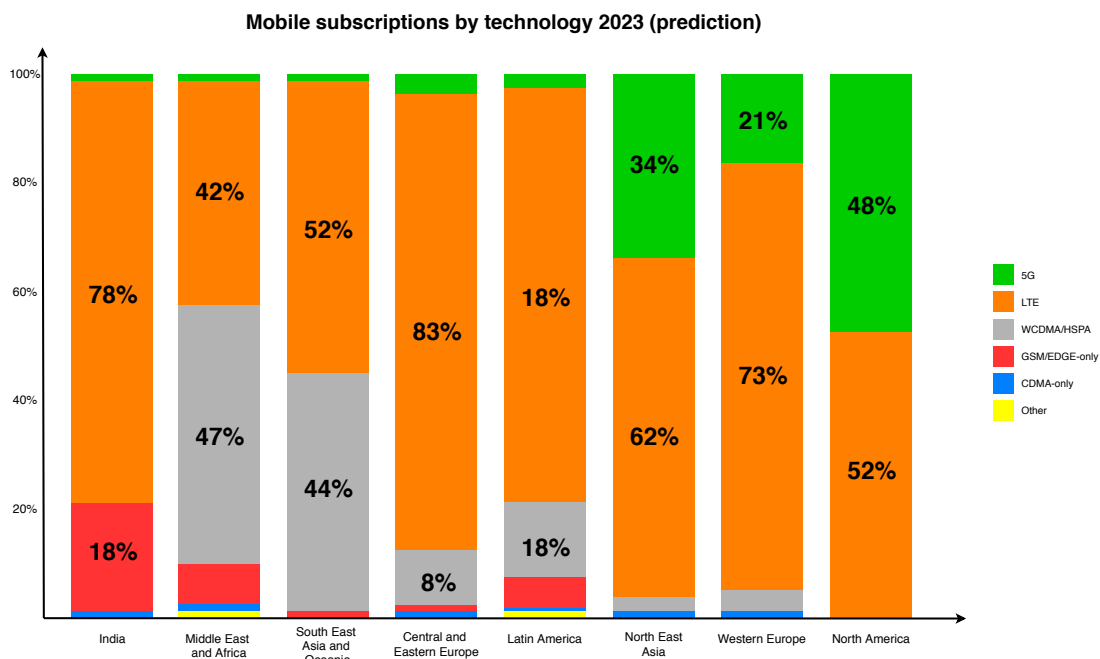


Figure 2.8: Mobile Subscriptions Prediction 2023 [8]

2.2.3 1st Generation Network (1G)

First-generation Cellular Technology (1G) cellular systems were the first cellular network and were initially developed by the United States, Japan and Europe in 1979-1983. Its primary feature was voice services and made use of analog modulation techniques. These were different from the initial mobile communications as the cellular concept showcased automatic switching and handovers to towers during calls. The world's first cellular implementation was done by Nippon Telephone and Telegraph Company (NTT) from Japan in 1979. Although Japan had already deployed its network, the first cellular network deployed in Europe was in 1981 by Nordic Mobile Company (NMT) and supported automatic handover and international roaming. The most successful deployment of the 1G networks was done by the United States using Advanced Mobile Phone Service (AMPS) followed by Europe and Japan with its Extended Total Access Communications System (ETACS) and Narrowband Total Access Communications System (NTACS). The 1G networks all had the same standpoint, which was that all networks were based on Frequency Modulation (FM) voice modulation, using Frequency Division Multiple Access (FDMA) for Multiple access and

Frequency Division Duplex (FDD) for duplexing. Most of the early cellular systems were designed with a Carrier-to-Interference Ratio (CIR) of 18dB for the sake of voice quality, and the system was deployed in a seven-cell frequency reuse pattern with three sectors per cell. Table 2.10 summarises when and by whom the different 1G networks were deployed with some differences to note in these early deployed cellular networks [18].

Table 2.10: 1G Network Deployments Summary [18]

	AMPS	ETACS	NTACS	NMT-450/900
Year	1983	1985	1988	1981
Channel Bandwidth	30kHz	25kHz	12.5kHz	25kHz/12.5kHz
Number of Channels	832	1240	400	200/1999

2.2.4 2nd Generation Network (2G)

2G networks were aimed towards the voice market but later in its development data related services were added. The key difference from 1G to 2G is the fact that it used digital modulation instead of analog modulation. This shift contributed to improvements such as the system capacity, and voice quality. 2G systems also used simple encryption to provide security against fraud and call droppers, which was one of the significant concerns in 1G technology, and in modern days network encryption is essential especially when using data services.

2G cellular networks consists of three technology types, GSM, IS-95 Code Division Multiple Access (CDMA) and IS-136 Time Division Multiple Access (TDMA). GSM is the most widely deployed, whereas IS-95 was deployed in North America and parts of Asia. IS-136 was a digital variant of the 1G AMPS system and was initially deployed in North America before it was discontinued and replaced by GSM systems. Currently

in Africa 2G and GSM is still the main cellular networks available.

The core feature that stood out from 2G in comparison to 1G was the improved voice quality, capacity and security. 2G introduced new applications such as the Short Messaging Service (SMS) for basic text communication. This can also be seen as the start and idea of data gathering for monitoring. The SMS application was firstly implemented in Europe in 1991 and became very popular with the young mobile subscribers as SMS had a significant cost advantage compared to voice. In addition to the SMS service supported circuit switch data services and later moved to the packet data service which is well known and is still used today. First data services had limitations regarding data rate and availability of space on the network. This problem led to the design of Wireless Access Protocol (WAP) which was used to deliver internet content to most devices [18]. Table 2.11 shows the summary of the 2G networks deployments and its key differences.

Table 2.11: 2G Network Deployments Summary [18]

	GSM	IS-95	IS-136
Year	1990	1993	1991
Channel Bandwidth	200kHz	1.25MHz	30kHz
Data Evolution	GPRS, EGDE	IS-95-B	CDPD
Peak Data Rate	GPRS: 107kbps EDGE: 384kbps	115kbps	12kbps
Latency	600-700ms	>600ms	>600ms

2.2.5 3rd Generation Network (3G)

While 2G networks brought increases in voice capacity, quality and support for data applications, there was a problem as data support was prolonged and inefficient as it

could only support low data rates such as tens of kilobits a second and had limited capacity. The solution to this was the third generation networks which were designed to have higher data rates, a significant increase in voice capacity and even supported multimedia type applications. The design of the 3G network was conducted in 1990 when the ITU began with invitations to 3G development. According to the ITU, 3G networks were supposed to create a globally harmonised specification for mobile communication with global interoperability and provide lower costs. The data services criteria for a 3G network included downlinks of:

- 2Mbps for fixed or in buildings.
- 384kbps in urban environments.
- 144kbps in wide area vehicular environments.

However, 3G networks were not just about high data rates but also provided a better Quality of Service (QoS) in applications from voice, interactive games, web browsing, email and streaming.

As with 2G systems, there were different proposals for the 3G systems, and interestingly most of these proposals used CDMA as the preferred access technique. The 2G IS-95 camp proposed an evolution toward a CDMA 3G technology called CDMA 2000, but GSM offered its version called Wideband Code Division Multiple Access (WCDMA). Later, the evolution of IS-95 was proposed and accepted by the 3GPP and is known as Evolution-Data Only (EV-DO) [18]. A combination of these different 3G technologies is still the core cellular network of Africa combined with that of the 2G cellular networks. Table 2.12 shows the summary of the 3G networks deployments with its key differences.

Table 2.12: 3G Network Deployments Summary [18]

	W-CDMA	CDMA 2000	EV-DO	HSPA
Year	2000	2001	2001	2002-2004
Channel Bandwidth	5MHz	1.25MHz	1.25MHz	5MHz
Data Modulation	QPSK,EGDE	BPSK, QPSK	QPSK,8PSK, 16QAM	QPSK,16QAM, 64QAM
Peak Data Rate	384-2048kbps	307kbps	DL:2.4-4.9Mbps UL:800-1800kbps	DL:3.6-14.4Mbps UL:2.3-5Mbps
Latency	100-200ms	500-600ms	50-200ms	70-90ms

2.2.6 4th Generation Network (4G)

The 4G network is also known as beyond 3G and is classified as the evolution of wireless communications. 4G network planning started in 2009 and is an entirely IP-based cellular network. It is the successor to the 3G network [18], [53]. In the release of 4G networks, not all cellular providers met the standards of the 3GPP for 4G, and although these networks were advertised as 4G, they were below the standards and considered as stop-gap measures. These 4G networks were called 3.9G because they differed from the 3GPP standards for a 4G cellular network. Most of these 3.9G networks are still active as they were the first 4G networks to rollout. In Table 2.14, a comparison of the beyond 3G networks are compared to the 3GPP standard for 4G, to see where these networks deviated [54].

4G networks represent a significant evolution from the 3G standards set by the 3GPP. The key improvements were removing the IP address limitations, increasing data transfer speeds and smoother handover, not just internally but to other operators and is notable in today's 4G networks when compared to 3G. Within 4G networks, two technology variants were submitted to the 3GPP as candidates for 4G. This was LTE and

LTE-Advanced (LTE-A), and these two networks were described as true 4G, and their specifications met the 3GPP standard. Table 2.14 shows how these two 4G network technologies differ.

2.2.7 5th Generation Network (5G)

In the evolution of cellular technologies, there was a significant shift in focus, as voice was the centre of mobile telecommunications up until 3G. When 4G was introduced, there was a paradigm shift to data-centric mobile telecommunications, and as usage patterns shifted from 3G to 4G, a rapid improvement in data transmission speeds has also happened. Cellular service providers offered new services and customised the customer experience on its networks. Technology is evolving fast, and cellular networks should keep up. As IoT is emerging a new 5G network is in its development, and it is nearing the end of its testing phase as it gears for deployment [55].

As with all newly developing cellular technologies, there are specific technical requirements to be met. The 5G network technical requirements are far better, and it is broken up into six categories which are seen in Figure 2.9.

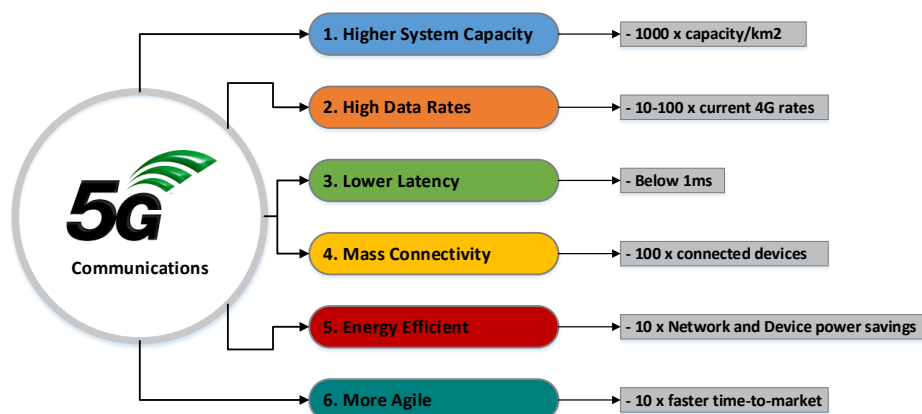


Figure 2.9: 5G Network Requirements [9]

5G networks have excellent data capabilities and can handle unrestricted call volumes and infinite data broadcasts. 5G also offers faster and newer network speeds, as well

Table 2.13: 3.5G, 3.75G, 3.9G and 4G Network Comparison [18], [19]

	3.5G	3.75G	3.9G	4G
Year	2002-2004	2007	2009	2011
Channel Bandwidth	2x5MHz	5MHz & 10MHz	1.3,3,5,10 and 20MHz	20-100mHz
Technology Type(3GPP)	HSPA, HSDPA	HSPA+	LTE	LTE-A
Peak Data Rate	14Mbps	168Mbps	300Mbps	1000Mbps
Latency	80ms	<10ms	<5ms	<5ms

Table 2.14: 4G Network Deployments Summary [20], [19]

	LTE	LTE-A
Year	2009	2011
Scalable Bandwidth	1.3,3,5,10 and 20MHz	20-100MHz
Coverage	Up to 5km	Up to 5km Optimised in micro cells
Capacity	200 active users per cell	3 x more than LTE
Peak Data Rate	300Mbps	1Gbps
Latency	10ms	<5ms

as a cheaper network solution than LTE which is a crucial aspect to consider when rolling out new cellular infrastructure. 5G network planning began back in 2010 when LTE was just released, and by 2015, 5G was in its development phase. As of 2018 test on the 5G network was being conducted with the commercial release expected to be late 2019, but more towards 2020 [55]. When 5G is deployed in 2020, it will have a significant impact on everyday life and will be the ultimate communication platform for M2M, Machine-to-People (M2P) and People-to-People (P2P) communications.

2.2.8 Cellular Network Summary

As the sections above gave more understanding as to how cellular networks evolved until today it is clear that cellular networks are moving fast and that people should keep up with the technology. To put the 5G network into perspective, a comparison table is shown in Table 2.15, where all five network releases are compared with its deployment date, bandwidth, main differentiator and weakness. It is evident that 5G networks were designed for IoT and M2M connectivity, but as the 5G network is not mature other networks should be used to start the implementation of IoT to not fall behind with this rapid technology innovation.

2.3 Future Planning

The IoT market is already showing a global impact on the economy without being deployed globally yet. The economic impact by Gartner estimates a benefit of 2 trillion United States Dollar (USD) by 2020 [56], and McKinsey predicts growth of 4- 11 trillion USD by 2025 [57]. Thus there seems to be a consensus that IoT would have a tremendous impact on economies and the growth of countries and by all the papers read IoT is going to be a technology disrupt. As IoT applications have been deployed already, the next big step in IoT is the development of smart and secure IoT platforms, especially networks. Current networks would help fill the gap by a bridge between

Table 2.15: Cellular Network Comparison Summary [21]

Technology	1G	2G	3G	4G	5G
Year	1970-1980	1990-2004	2004-2010	2010-Current	2020
Data Rate	2Kbps	64Kbps	2Mbps	1Gbps	>1Gbps
Technology	Analog	Digital	CDMA 2000, UMTS,EDGE	Wi-Max, Wi-Fi,LTE	WWWW
Primary Service	Analog Calls	Digital Calls and SMS	Phone Calls, SMS, Data	All IP Services	High speed, High capacity, Large data broadcast
Key Differentiator	Mobility	Secure, Mass adoption	Better Internet experience	Faster Internet, Lower Latency	Better Coverage, No dropped calls, lower latency, Better performance
Weakness	Major Security issue	Limited data rates	Performance fail to match	High battery use Require expensive hardware	N/A

the future IoT driven networks and the older legacy networks, which is well-known and mostly used all over the world [58]. Gartner also predicts that by 2020, 80% of IoT applications would have failed due to improper IoT infrastructure and improper data collection methods which is one of the main concerns [56]. Data that is gathered needs to be represented in a fashion that users can relate and understand. The main problem with the future of IoT is the limitations and deficiencies of the current network infrastructure, especially when looking at less developed countries. These topics include security, interoperability and scalability. These topics would need extensive research as they are critical requirements for future IoT networks [58].

2.3.1 Future IoT Networks

The future network for IoT will be Sixth-generation Cellular Technology (6G). The Centre for Converged Terahertz Communication and Sensing (ComSenTe), is already working on 6G specifications. 6G networks are expected to have speeds of up to 100Gbps with the capability of up to 1000 simultaneous independent modulated beams [59]. Currently, a group of technologists at the Finland University of Oulu has started funding for their eight-year research programme called 6Genesis. 6G networks are still ahead of its time, and standards will only be finalised in at least ten years. The reason for the early research on 6G is that in 2030 the world's population is estimated to be 8.5 billion people, with IoT connections exceeding 125 billion devices. This number of devices will need a network that can provide speed and enough bandwidth for handling thousands of connections in a single cell.

6G will be used to revolutionise transportation, autonomous vehicles, platooning and intelligent roads. Cities will benefit from seamless, ubiquitous connectivity enabling constant information exchange between machines and humans. 6G will emerge around 2030, as new generations previously appeared every ten years, and it will satisfy all the expectations that were not met by the 5G network [59].

2.3.2 Future IoT Implementations

The Internet of things has many benefits, and some of them include, making life more comfortable, safe and smart. No one knows what the future holds, and there are many possible future applications of IoT. We are entering the 4th Industrial revolution and, M2M, IoT and Big Data play a vital role as seen in Figure 2.10, that shows what the 4th Industrial revolution requires [10].

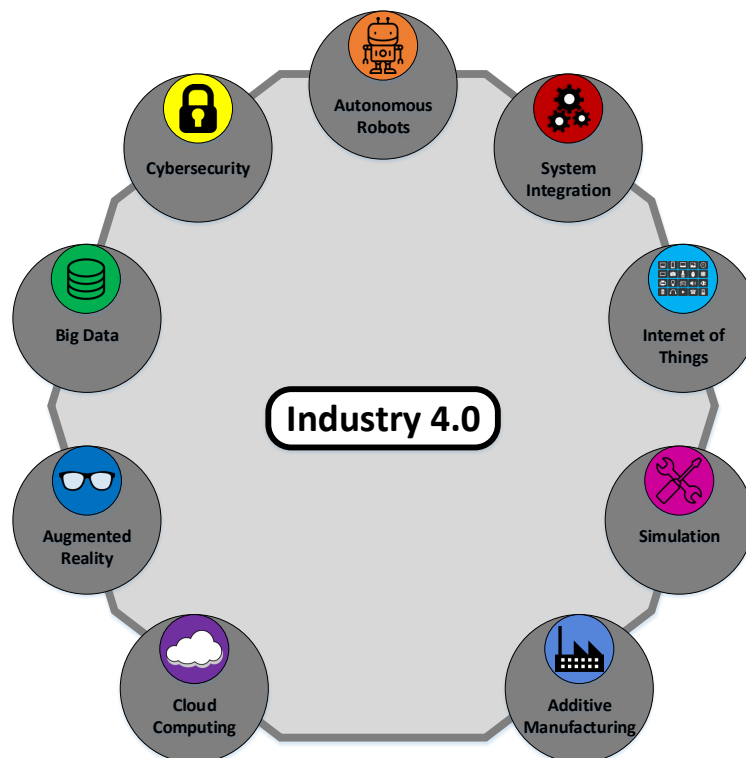


Figure 2.10: Future IoT Applications [10]

Many future technologies will be related to IoT as well as wireless control, communication and IT technologies. These should work seamlessly together as all application should be able to communicate and share its gathered data on a stable platform. The possible future IoT applications include: Smart Cities, Smart home and buildings, Smart energy and smart grid, Smart health, Smart transportation and mobility, Smart factory and Smart manufacturing and Smart environments [10].

IoT applications would become part of everyday life, and new applications would be targeted for specific use cases and become real in our lives. This will enable us to become part of everything around us, such as Smart healthcare, Smart homes and other Smart applications.

2.4 Related Work

There are numerous studies regarding cellular IoT and the implementation thereof. Although some technologies like Sigfox and NB-IoT are based on cellular networks, most of these studies focus solely on LTE cellular networks for IoT implementation. The capacity estimation exercise is approached using Mobile Autonomous reporting (MAR) and Network command. The LTE network capacity is expressed in terms of the number of reports per physical resource block (PBR) per hour. IoT applications such as road monitoring and non-residential services, reports data faster and requires the use of more PBR's per hour [23].

Another approach to capacity estimation on an LTE network was made in terms of low data rate applications and high data rate applications for both urban and suburban cases. The capacity estimation (N) was calculated using the allocated time (T), cellular data rate (DR_{cell}) and payload size (P_{APP}) shown in Equation 2.1. For low data rate applications, NB-LTE (Narrow Band LTE) would be best suited, but in the case of high data rate applications such as traffic management, LTE solutions could be taken into account [50].

$$N = \frac{DR_{cell}T}{P_{APP}} \quad (2.1)$$

In another paper the same PBR method was implemented, this time LTE cellular network was used for IoT deployment, and a capacity estimation was done for both LTE and NB-LTE networks since NB-LTE systems are built from existing LTE functionalities. NB-LTE, however, interferes with the LTE network and can cause coverage prob-

lems using co-channel interference and adjacent cell interference. NB-LTE cannot yet be incorporated in current LTE infrastructure [60].

LTE can support large numbers of IoT devices, that would have limited impact on daily cellular traffic. It was found that the average number of devices an LTE cell can handle is 52547 [23].

All these related work studies have valid methods, and conclusive results that supports 4G cellular networks can implement IoT applications. As mentioned in Section 2.2.2, Africa has a low 4G network coverage range with most of the network releases being 2G and 3G networks. This resulted in using an Erlang approach for 2G and 3G networks as well as applying the Erlang method to the 4G networks to estimate the number of IoT devices that could be supported by existing African cellular networks.

2.5 Concluding Remarks

IoT is an emerging topic, and for a IoT device to be implemented, there has to be applications and a network that support these billions of devices. Currently, IoT is divided into categories, and each of these categories has various applications that form part of M2M communications. By connecting all IoT devices, a smart city can be created which would in turn benefit, citizens, transportation and services in a city.

With SSA being the least ready to implement IoT, there are IoT networks that can flourish in Africa such as LoRa, Sigfox, EC-GSM-IoT, NB-IoT and LTE-M. All of these technologies would have significant capital expenditure associated with their deployment. Thus, for Africa, attempting to leverage existing (possibly even legacy) infrastructure might be the way forward.

Cellular Networks consist of 1G, 2G 3G, 4G and 5G, and the difference between each generation network is remarkable. In SSA however, from 2014 until 2017, more than 50% of the network infrastructure is still on the 2G and 3G level.

Africa as a whole might be lacking behind in network infrastructure, but there are current deployments of IoT across Africa, where existing cellular infrastructure is used. This poses for smart application such as smart traffic monitoring and management as South Africa has a concerning problem as well as many other countries in Africa.

Future IoT networks will include 5G which should be commercialised by 2020, and then the possibility of 6G by 2030. As the generation of cellular technology evolves so will the applications of IoT devices.

Chapter 3

Model Development and Verification

This chapter covers the model development, which includes the system model explanation, model implementations as well as the verification of the system model. The chapter concludes with remarks regarding the verification of each step of the system model and the implementations thereof.

3.1 Methodology Overview

The methodology of this study is integrated into the system model, and each of the steps mentioned in this overview is fully explained in its section in this chapter. The first step of the methodology is a prerequisite check. In the case of this capacity estimation study, a cellular network was chosen as the network for the IoT deployment with the case study of smartly connected traffic lights. This study could only be viable if all the traffic lights fall within the cellular coverage. The following steps are an overview of how the methodology in this section follows and how each step is implemented:

- Plot a cellular network coverage map of Potchefstroom using the crowdsourced data of signal strength.
- Plot the traffic lights in Potchefstroom to ensure complete cellular coverage over all traffic lights.
- Calculate the cellular network capacity and determine the unutilised network space in Erlang.
- Calculate the minimum and maximum network requirements for a single IoT device in Erlang.
- Calculate the estimate IoT device supported by a single cell in a network by dividing the unutilised network space in Erlang with the single IoT device requirements.
- Represent the estimated minimum and maximum IoT device as a range.
- Conclude whether the solution is viable.

3.2 System Model

From the literature study, it became apparent that the extent to which the existing infrastructure could be leveraged to support the IoT needed to be determined. Given that cellular networks are prevalent in Africa, it made sense to leverage any unused network capacity for IoT deployment. In this case, the specific IoT deployment will focus on improved vehicle traffic management through intelligent traffic lights.

In this chapter a model is developed that will estimate the capacity of existing cellular infrastructure to support IoT devices. This is done by using the Erlang method and standard cellular network capacity equations. By applying these formulae to IoT devices as if they were mobile phones replicates an excessive number of calls being made from an IoT device over a cellular network. Figure 3.1, is a flow diagram of the model and is a graphical representation of the methodology overview given in Section 3.1.

The system model is divided into 3 sections where which will be used to simplify the explanation of the system model:

- Section A - Cellular network capacity.
- Section B - Cellular capacity required for an IoT device.
- Section C - Estimate IoT device that the cellular network can handle.

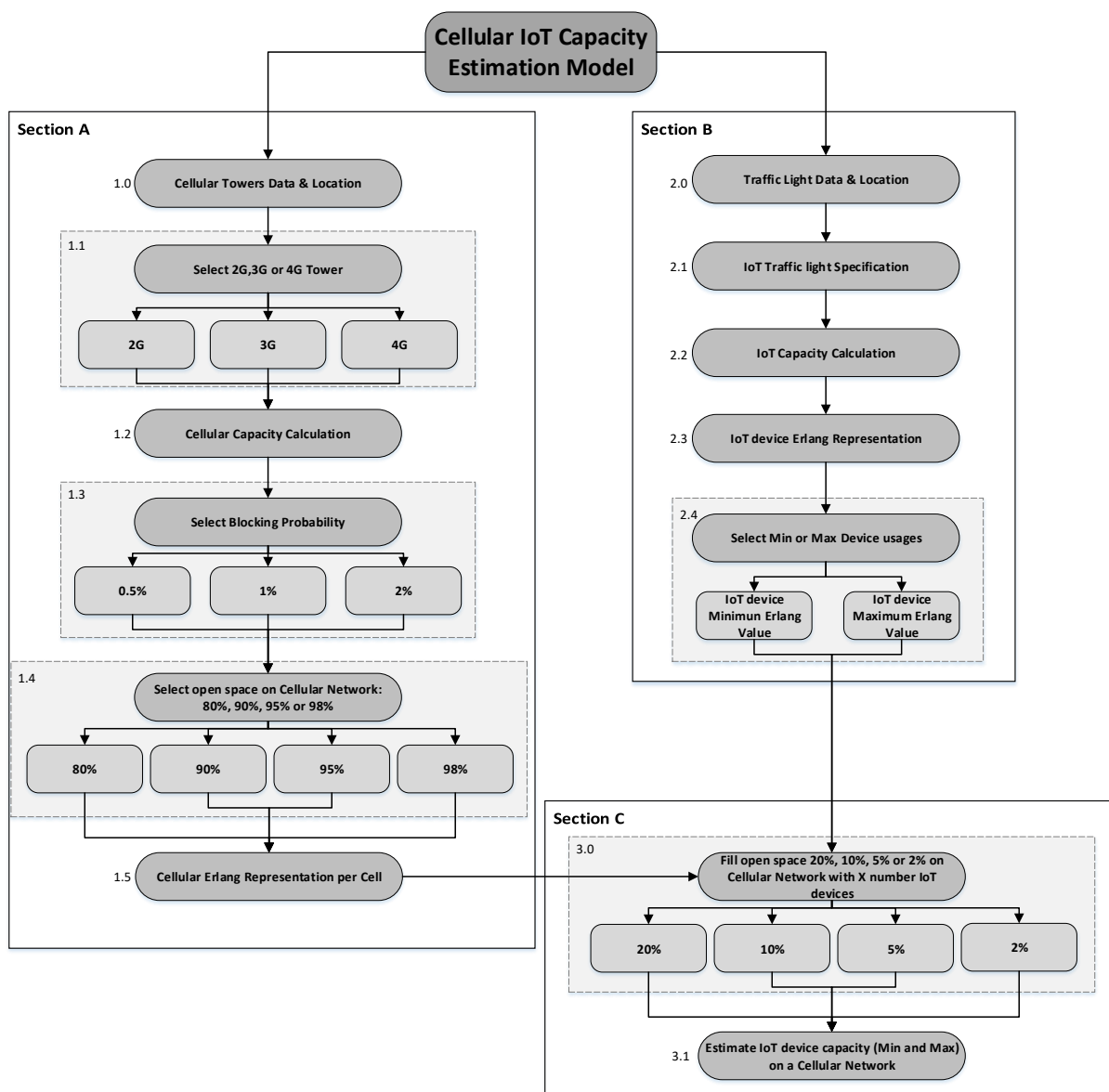


Figure 3.1: System model Block Diagram

The model starts at Section A with block [1.0], where the cellular towers Global Positioning System (GPS) location and specification data is gathered. The first selection block is [1.1], where all the data from the various cellular tower is divided into cellular technology generations 2G, 3G and 4G. Block [1.2] is where the average capacity per tower for each network generation is calculated. Block [1.3] now provides a selection of 2%, 1% and 0.5% blocking probability for cellular device connections. The selection comes from the Erlang B table, which can be found in Appendix A.1. Block [1.4] is where the Erlang value of the unutilised cellular capacity gets calculated, to determine the Erlang network capacity for IoT devices. The towers are assumed to either be at 80%, 90%, 95% or 98% utilised capacity. In block [1.5] the utilised capacity on each of the different generation network towers is calculated with the different blocking probabilities. This is done for each network generation and represented as an Erlang value.

Now moving to Section B, the case study for IoT implementation is smart traffic lights. Block [2.0], is where the data and GPS locations of the cellular towers must be gathered with the different traffic light specification. In block [2.1] the IoT specifications for maximum demand and minimum capacity demand are gathered. Block [2.2] now uses the specifications of the IoT traffic light to calculate the capacity needed by an IoT device, and in block [2.3] this capacity value is expressed as an Erlang value. Block [2.4] expresses the maximum and minimum capacity needed for a single IoT, as an Erlang value.

Now focusing on Section C. Block [3.0] is where the results from blocks [1.5] and [2.4] come together to estimate the number of IoT devices that can occupy the remaining network capacity of either 20%, 10%, 5% and 2%. Concluding the system model with block [3.1], the unutilised network capacity is occupied with an X number of IoT devices. Thus a minimum and a maximum estimate of IoT devices that can occupy the unutilised network capacity is expressed as an estimated range.

3.2.1 Capacity Estimation Model

The estimated capacity of IoT devices is dependent on the capacity of each cellular tower. Before any estimation regarding IoT devices can be approached the capacity of each cellular tower must be calculated. Cellular towers have different specifications as each carrier that operates the cellular network to their needs. Despite having different specifications, the geographical area of the tower has a significant effect when it comes to the coverage and capacity of the network. The specifications of cellular towers are classified data and cannot be requested from cellular providers. In this study, specifications from the ITU and average values gathered from towers, CellMapper [61] and OpenCellid [62] is used to calculate the capacity of each cellular tower in the different technology groups; 2G, 3G and 4G.

Cellular Capacity Model

The capacity of the cellular towers is calculated, but the capacity of the towers is not necessarily fully utilised. Knowing the parameters of an IoT device the unoccupied space on the cellular network can be allocated to IoT devices. The estimated number of IoT devices is calculated by approaching cellular tower usage with the Erlang traffic model. This system model is described in Figure 3.2 and the IoT application used in this study is smart traffic lights [63], [64].

The cellular capacity of each tower is calculated by using the average number of traffic channels (T). The cluster size (K) of the cellular tower can change depending on the environment (path-loss coefficient (α)), carrier to co-channel interference ratio ($\frac{C}{I}$) and the geographic location of the cellular tower. Thus $K=1,3,4,7,9,12,21$ which is demonstrated by Figure 3.3 and can easily be calculated by the use of Equation 3.1. The number of traffic channels per cell (N) is calculated using Equation 3.2 knowing the total channels (T) [63], [64].

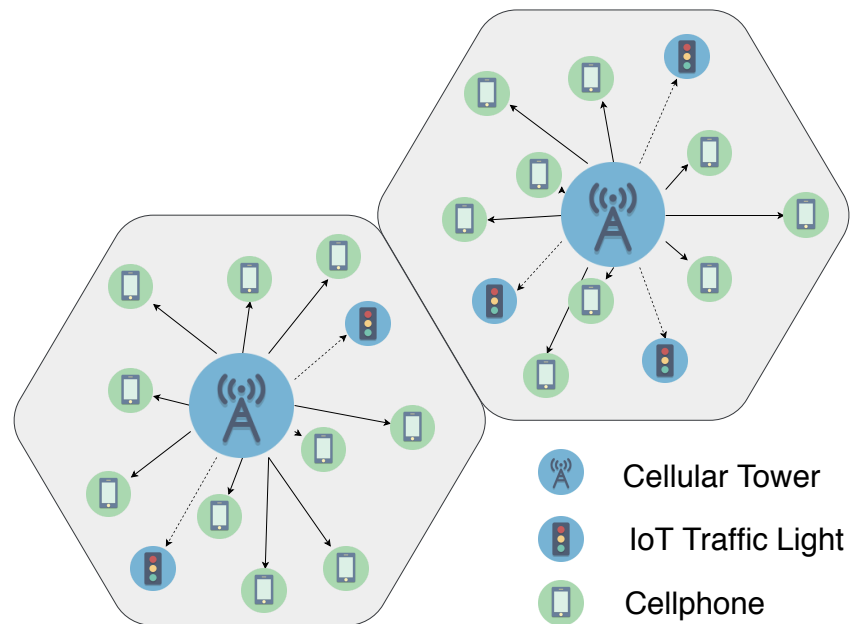
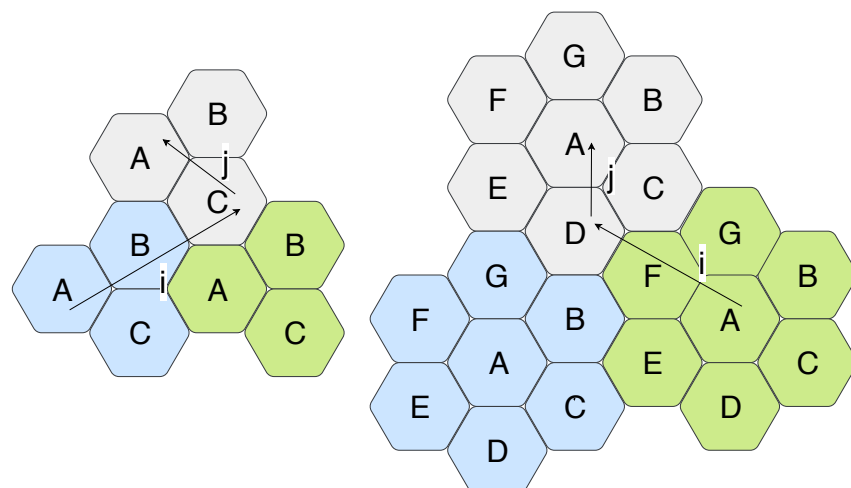


Figure 3.2: IoT traffic system model

Figure 3.3: General cluster representation for $k=3$ (left) and $k=7$ (right)

$$K = i^2 + ij + j^2 \quad (3.1)$$

$$N = \frac{T}{K} \quad (3.2)$$

The capacity of the cellular system is calculated with Equation 3.3 that uses the number of traffic Channels (T) multiplying it with the number of times the cell cluster repeats itself (M), as in Figure 3.3 $M=3$ in both examples [63], [64]. M and T are directly proportional, where M indicated the coverage area by the number of times the cell cluster repeats itself. In this study, crowdsourced data was used, and the actual M and T values were unknown; however, average values gathered was used.

$$SystemCapacity = M \times T \quad (3.3)$$

Equation 3.7 is used to calculate the minimum cluster size (K) required for the geographical location of the cellular tower. Equation 3.7 is a combination of the co-channel reuse ratio ($\frac{d}{r}$) shown in Equation 3.4, the path loss exponent shown in Equation 3.5 and the carrier to co-channel interference ratio ($\frac{C}{I}$) shown in Equation 3.6. Thus combining these equations results in the minimum cluster size required for a cellular tower and its parameters [64].

According to [65], a propagation model is used to predict average signal strength at a distance from the transmitter as well as the variation of the signal strength near the transmission tower. Various propagation models could have been implemented in this study such as: Free space, Longley-Rice, ITU-R P.370-7, Okumura-Hata and Walfish-Ikegami. However, as the primary focus of this study is the capacity estimation of a cellular network developed from crowdsourced data it is not known what propagation model is used by each carrier. Thus the basic explanation of a free space propagation model is used to explain how cellular calculations rely on a propagation model and more specifically what role the path loss constant plays in the propagation

model [66]. In cellular networks, the path loss is expressed in dB, and it is the attenuation undergone from electromagnetic waves in transit between the transmitter and receiver [67]. This value of the path loss constant is highly dependent on the location of the tower and the area it should cover. The path loss constant in open space is much lower than compared to towns with buildings as there are fewer obstructions for the cells to broadcast its signal. Table 3.1 shows constant values that are used for basic cellular path loss calculations. This, however, is just an indication of typical path loss for that specific scenario and can still vary due to natural and external factors [22].

Table 3.1: Path Loss Coefficients [22]

Environment	Path Loss Coefficient (α)
Free space	2
Urban area cellular radio	2.7 - 3.5
Shadowed urban cellular radio	3 - 5
Inside a building - Line of sight	1.6 -1.8
Obstructed in building	4 - 6
Obstructed in factory	2 - 3

$$\frac{d}{r} = \sqrt{3K} \quad (3.4)$$

$$P_r = P_t L d^{-\alpha} \quad (3.5)$$

$$\frac{C}{I} = \frac{P_t L_r^{-\alpha}}{\sum_{j=i}^6 P_t L_d^{-\alpha}} = \frac{1}{6} \left(\frac{r}{d} \right)^{-\alpha} \quad (3.6)$$

where: P = Power in dBW, L = constant depending on frequency, d = distance in m, and α = path-loss coefficient

$$K = \frac{1}{3} \left(\frac{6C}{I} \right)^{\frac{2}{\alpha}} \quad (3.7)$$

The typical $\frac{C}{T}$ value for digital networks are 13-18dB, and α is the path-loss coefficient that is determined by the geographical location of the cellular tower and in the case of this study the most common path loss constant used in Africa is that of free space and Urban areas, whereas the occurrence of free space is more likely [64].

It is noted that there is an interdependence between $\frac{C}{T}$ and K in Equation 3.7 as well as K and T Equation 3.2. This makes $\frac{C}{T}$, K and T interdependent of each other. As crowdsourced data was used in this study the typical values for $\frac{C}{T}$ according to [64] was used.

IoT Traffic Light Estimation Model

With the case study of the IoT implementation being intelligent traffic lights, an overview of how the intelligent traffic light model should work is discussed with the help of Figure 3.4.

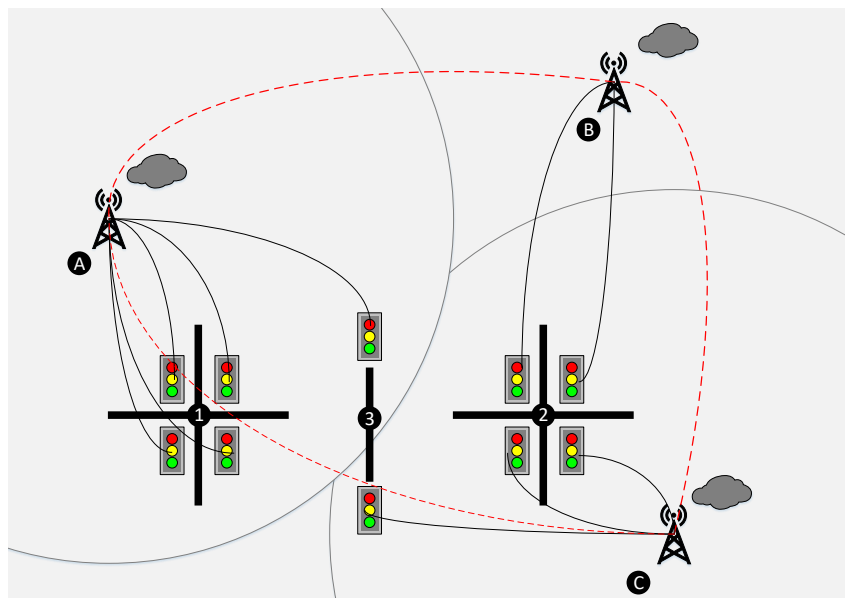


Figure 3.4: IoT Traffic Light Model

In Figure 3.4, three cellular towers (A, B and C) can be seen, each with its radius of cellular coverage. Intersections [1] and [2] are regular 4-way intersections with intersec-

tion [3] being a pedestrian crossing. The coverage of all three cellular towers overlaps one another, thus having a means of M2M communication.

Now focusing on cellular tower [A], the whole intersection [1] and one traffic light from intersection [3] falls within the coverage of tower [A]. Cellular tower [B], only connects 2 traffic lights from intersection [2]. Lastly, cellular tower [C] connects the remaining two traffic lights from intersection [2] as well as the other traffic light from intersection [3].

By looking at Figure 3.4, all the traffic lights could have been connected to cellular towers [A] and [C] only. However, these two cellular towers are at full network capacity. Thus as tower [B] has unutilised network capacity, two traffic lights from intersection [2] are connected. This ensures that all the traffic lights are connected to this cellular network. This is just a basic diagram that explains the concept of how IoT traffic lights are suggested to work in this study.

According to [68], the average time a traffic light takes to transition from state ranges between 2s and 120s. These experimental IoT device parameters are found in Table 3.2 and was used for the calculations regarding the amount of space an IoT device would consume on a cellular network in its minimum usage and maximum usage cases.

Table 3.2: IoT Device Experimental Parameters

Parameter	Range
Tx Interval	2s - 120s
Tx Time	20-30ms
Payload	256KB
Data Rate	64kbps (2G) - 1Gbps (4G)

The calculated cellular capacity is expressed i.t.o Erlang and the IoT device requirements were also approached using the Erlang method, typically found in cellular calling calculation. Erlang is a unit of measure for telecommunication traffic and describes

the traffic volume of one hour. An IoT device is seen as a device making short calls over an hour (transmission of data per hour). These cellular capacity Erlang values are used to determine the estimated IoT devices that can work on a cellular network.

Now as illustrated in Figure 3.5 cellular towers have a fixed capacity which is utilised by mobile users. Any cellular network has unutilised space on the network; thus there is an opportunity to connect an X number of IoT devices on the utilised network capacity. The unutilised space is now occupied with an X number of IoT devices dependant on the IoT application. Applying this method, current cellular network infrastructure can be utilised to implement basic IoT needs and services in an African context.

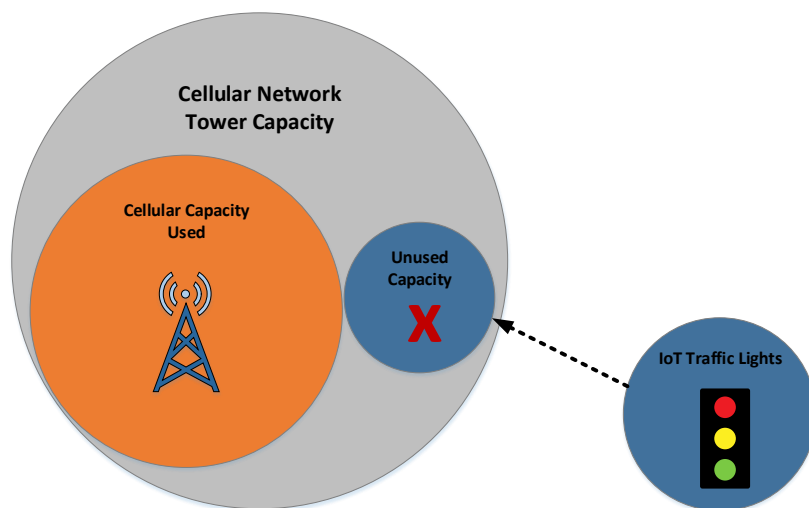


Figure 3.5: IoT Capacity Estimation Model

To determine the unutilised network capacity that can be occupied on the cellular network, the IoT capacity estimation model uses the Erlang traffic approach. The Erlang value for the maximum traffic a cellular tower can handle is read from the Erlang B table that is attached in Appendix A.1, where an average number of traffic channels is used to find the maximum Erlang traffic a cellular tower can handle. The IoT device Erlang requirements are calculated with basic IoT device parameters such as the transmission arrival rate (transmissions/hour) and mean holding time (hours/transmission) in Equation 3.8 [64].

$$E = n\lambda t_h \quad (3.8)$$

where: n = number of devices, λ = transmissions/hour and t_h = hours/transmission

Dependent on the unutilised cellular capacity on the cellular tower the IoT devices can now start occupying the network, and according to the Erlang value of the cellular tower and multiplying the Erlang value of a single smart traffic light, the minimum and maximum IoT devices that can be connected to a cellular tower is estimated and expressed as a range.

3.3 Model Implementations

3.3.1 Simulation Tools

There are a few software tools that were used in this study. The cellular tower data and traffic light data was gathered by using CellMapper [61], OpenCellid [62] and Google Maps respectively. This was handled and sorted in Microsoft Excel and formatted for the study using Python.

The cellular tower location data and traffic light location data was used in MATLAB in conjunction with the Mapping toolbox and a web map application. The Mapping toolbox was used to plot the location of the cellular towers as well as the traffic lights in Potchefstroom, South Africa.

The MATLAB antenna toolbox was used simultaneously with the Mapping toolbox for plotting the cellular coverage maps. Moreover, MATLAB was used for all the calculations regarding capacity estimation. Each of these tools and their implementations in this study will now be discussed.

- **MATLAB** - Was used with the Mapping toolbox and Antenna Toolbox, but the primary use of Matlab was for the cellular tower capacity calculation. Each technology generation 2G, 3G and the 4G cellular specification was used from the python formatted data to calculate the capacity of the average cellular tower for each technology. These values were used to express each cellular towers capacity capabilities in Erlang with different blocking probabilities. The next calculations were done by using the researched data for IoT devices and the busy hour traffic model to express the minimum and maximum Erlang value each IoT device would require. This required IoT Erlang value was substituted into the unutilised network space, and an estimated range of device for each technology towers was calculated. All the formulae used to achieve these results is given in Section 3.2.
- **Mapping Toolbox** - The toolbox was used to display the map of the traffic lights which would be used as the IoT devices in this study. The location of the cellular towers was also shown using this toolbox.
- **Antenna Toolbox** - The antenna toolbox is a toolbox within Matlab, that can plot the coverage areas when given the signal strengths of each tower. The crowd-sourced data of signal strengths were used together with the GPS location of each known tower in the area to show an estimate coverage map of the towers. This was done for 2G, 3G and 4G networks as well as estimate coverage maps for the four different network carriers in South Africa. This was done as a step to check whether all the traffic lights fall within mobile coverage before continuing with a possible solution.
- **Python** - The crowd sourced cellular data file from OpenCellid contained data gathered from all over the world with a mobile Android application, thus having an excel file of 3Gb in size. As it is merely impossible to extract the data manually from excel, a python script was written to extract the data for the Potchefstroom region in South Africa. This was done by defining a search block consisting of top and bottom latitude coordinates as well as a left and right longitude coordinates. As this was a large data file the readline command was used to read the file line for line and to extract any values that fall within the search block parameters. The

output was written to a new excel file, and the cellular tower coordinates were verified using Google Earth. The primary reason for choosing Python as a data handling tool was because of its properties to read through the data line by line.

3.3.2 Cellular Network Coverage

As a case study, the IoT capacity is estimated with the cellular coverage information for the town of Potchefstroom. MATLAB and specifically the antenna toolbox was used to overlay cellular coverage maps and IoT devices.

Cellular Specifications

Firstly the cellular information is needed to plot the coverage maps i.t.o 2G, 3G and 4G coverage. This coverage map is also plotted for the four leading cellular providers in South Africa. The average values across the four carriers of the cellular data gathered were used for the capacity calculations and coverage maps. These experimental parameters is summarised in Table 3.3 and Table 4.1 [52], [49], [48]. Some acronyms used in the tables: transmitted power (tx) and Bandwidth (BW).

Using the equations from the system model and values from Table 3.3 and Table 4.1 the coverage maps and cellular tower capacity is calculated. All values used as specifications are according to the standards in South Africa, and only the signal strength value is an average of the different network carriers data for 2G, 3G and 4G.

Table 3.3: Potchefstroom Cellular Tower Experimental Parameters

Parameter	2G	3G	4G
Tx Power	20W	20W	20W
Antenna Height	15-30m	15-30m	15-30m
Signal Strength	Min:-53dBm Max:-89dBm	Min:-55dBm Max:-107dBm	Min:-68dBm Max:-106dBm
BW	200KHz	5MHz	10-15MHz
Data Rate	64kbps	144kbps- 2Mbps	100Mbps- 1Gbps
Frequency Band SA	900MHz/ 1800MHz	900MHz/ 2100MHz	1800MHz/ 2300MHz

3.3.3 Cell Tower Locations

As this study makes use of crowdsourced data from CellMapper [61] and OpenCellid [62], the only data available to estimate the coverage range of the cellular towers was the average signal strength data of all the cellular towers. This average value was used as signal strengths can be depended on various factors such as trees, buildings, indoors vs outdoors as well as the distance from the tower [69].

Just as signal strength is dependent on various factors which is mainly its geographical position coverage maps cannot compensate for all these natural interferences. Coverage maps are an engineered projection of the actual and theoretical coverage of a cellular tower [69]. Just as a coverage map can have its inaccuracy if high signal strength is detected, it does not guarantee that there is a good connection, but there is a connection [70]. Knowing that there are decent signal strengths at certain points from the crowdsourced data an estimate cellular coverage map could be mapped to indicate where signal strengths were received. This was presented in the form of a coverage map and signal circles to ensure that all the IoT device falls within a coverage range

and also to ensure that this will be a viable solution for IoT deployment in Africa. These estimated signal strength maps will be referred to as the coverage map in this study.

The data from CellMapper [61] and OpenCellid [62], as well as the researched data regarding 2G, 3G and 4G cellular networks combined by location pinning in Google Maps, were used to generate the coverage map with MATLAB specifically the mapping and antenna toolbox. The crowdsourced data, calculation results and averaged values used for the coverage maps are summarised in Table 3.3 and Table 4.1 which will be discussed in the next few sections.

Cell Tower Coverage Mapping

The four leading cellular providers in South Africa was used to map the cellular coverage of Potchefstroom. The cellular data for each network with their technologies were filtered using Python before the data was imported into MATLAB and with the use of the Mapping Toolbox and Antenna Toolbox, the coverage maps were plotted. Each carriers coverage maps for the different technologies will be displayed in this section.

Network Provider A

Figure 3.6 shows the coverage maps of cellular provider A. In Figure 3.6 (a) the 2G network technology coverage is made up of 4 towers, Figure 3.6 (b) the 3G network technology coverage is made up of 14 towers and Figure 3.6 (c) the 4G network technology coverage is made up of 2 towers. Lastly, all the network technologies were grouped for Network Provider A and all 20 towers coverage was plotted in Figure 3.6 (d).

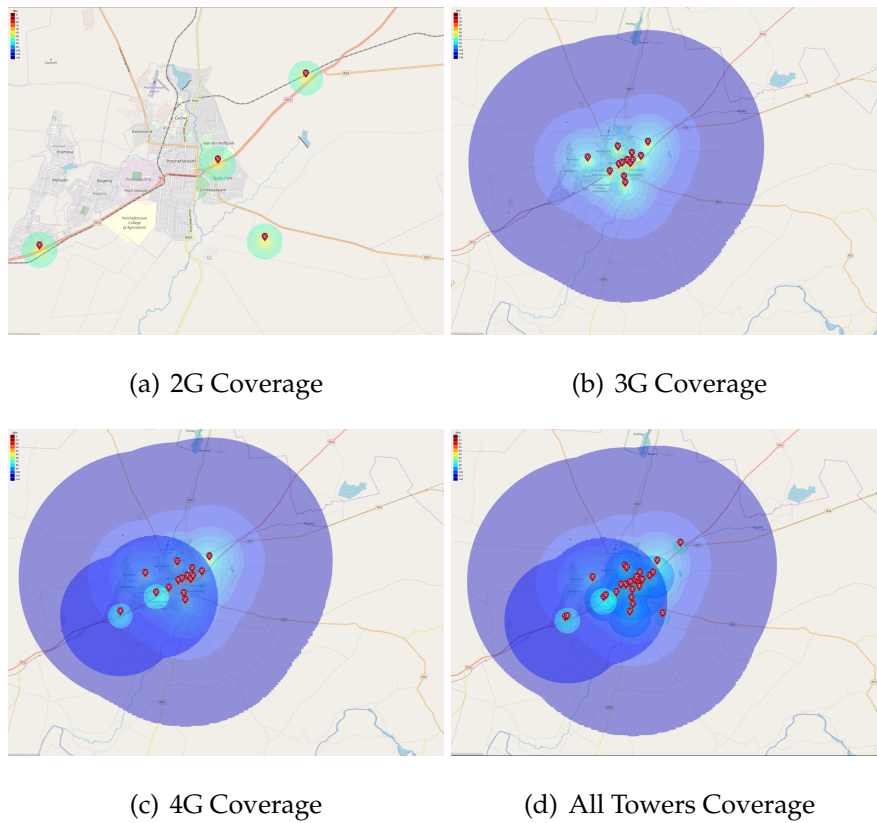


Figure 3.6: Network Provider A: 2G, 3G and 4G Cellular Coverage

It is however clearly shown that in the case of Network Provider A, the 2G coverage is minimal and the 3G and 4G coverage for Potchefstroom is the most effective for the provider.

Network Provider B

Figure 3.7 shows the coverage maps of cellular provider B. In Figure 3.7 (a) the 2G network technology coverage is made up of 4 towers, Figure 3.7 (b) the 3G network technology coverage is made up of 12 towers and Figure 3.7 (c) the 4G network technology coverage is made up of 5 towers. Again all the network technologies were groups for Network Provider B and all 21 towers coverage was plotted in Figure 3.7 (d).

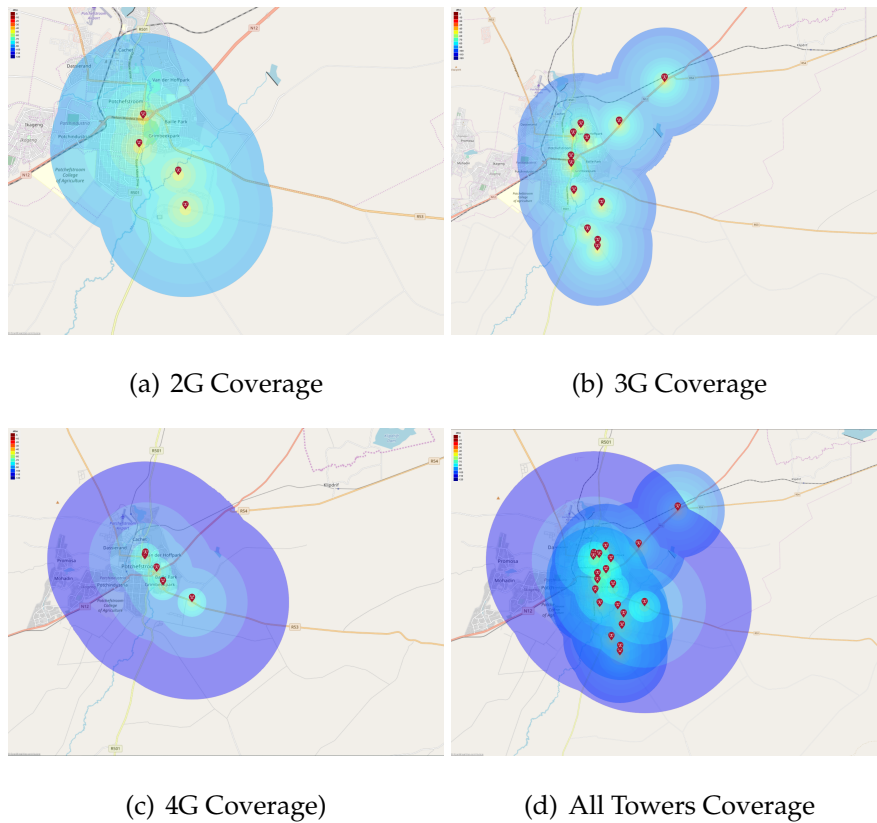


Figure 3.7: Network Provider B: 2G, 3G and 4G Cellular Coverage

Figure 3.7 shows that in the case of Network Provider B, the 2G coverage does not have a significant number of towers but good coverage. The 3G towers are the most prominent in Provider B, with reasonably good 4G coverage for Potchefstroom when compared to Provider A.

Network Provider C

Figure 3.8 shows the coverage maps of cellular provider C. In Figure 3.8 (a) the 2G network technology coverage is made up of 2 towers, Figure 3.8 (b) the 3G network technology coverage is made up of 7 towers, and there is no direct coverage for 4G networks by Network provider C. This does not mean that the networks do not have support for 4G, they probably roam on other network providers 4G network. The network technologies were groups for Network Provider C, and all 9 towers coverage

was plotted in Figure 3.8 (d).

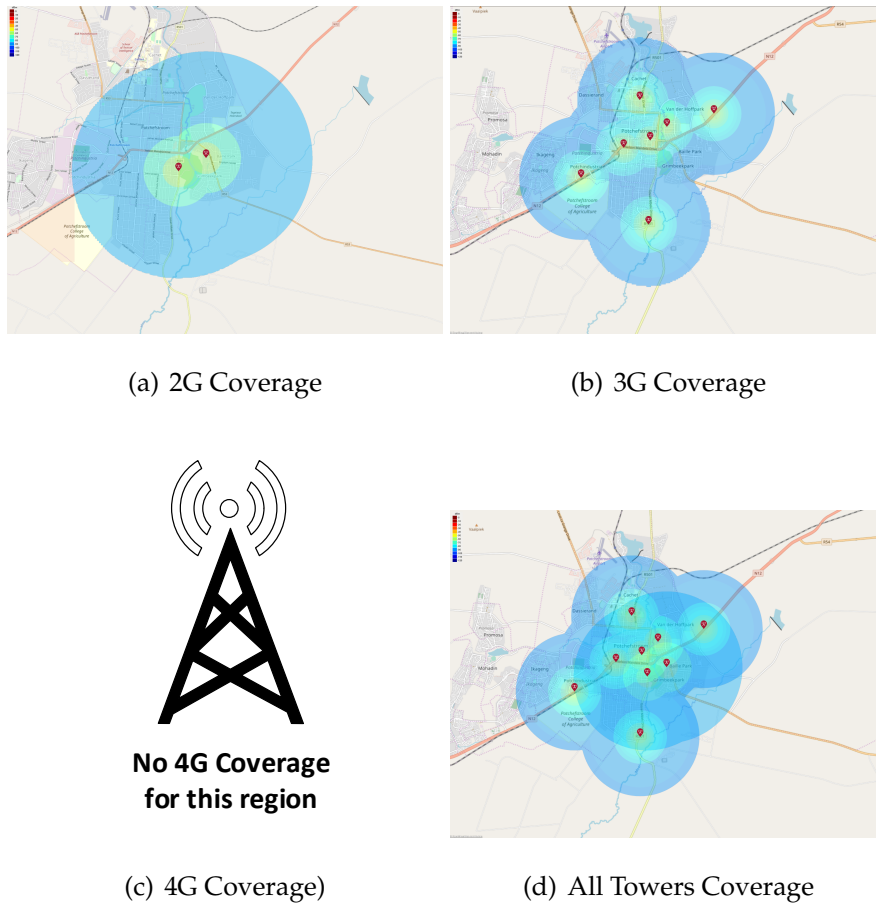


Figure 3.8: Network Provider C: 2G, 3G and 4G Cellular Coverage

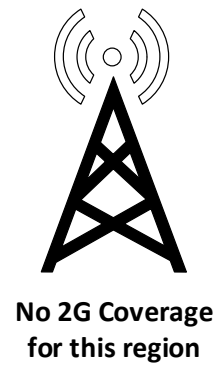
Figure 3.8 shows that Network Provider C has limited 2G coverage and the 3G network gives the most significant coverage as the network provider does not have any 4G coverage in Potchefstroom.

Network Provider D

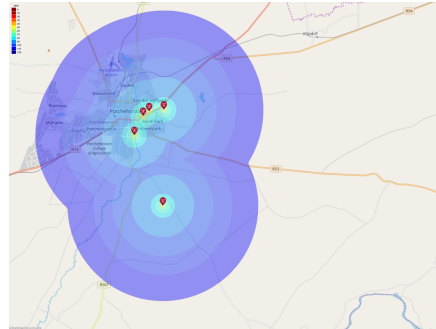
Figure 3.9 shows the coverage maps of cellular provider D. Network provider D does not have any 2G or 4G coverage. Thus Figure 3.9 (b) shows the 3G network technology coverage that is made up of 5 towers.

The network technologies were groups for Network Provider D which in this case is

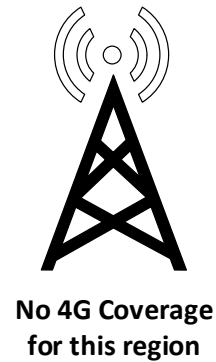
only the 3G towers. The coverage was plotted in Figure 3.9 (d).



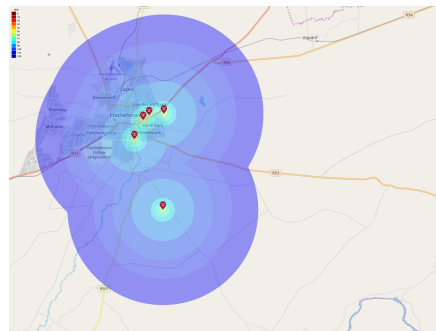
(a) 2G Coverage



(b) 3G Coverage



(c) 4G Coverage



(d) All Towers Coverage

Figure 3.9: Network Provider D: 2G, 3G and 4G Cellular Coverage

With only coverage with 3G networks, Network Provider B has the second best 3G coverage of all the network providers in Potchefstroom.

Network Technology

For the capacity estimation study, the average values from all four carriers were used and grouped in the technology groups. Thus Figure 3.10 shows the coverage maps of Potchefstroom as well as a coverage map of all the towers from the different carriers combined in Potchefstroom. Figure 3.10 (a) maps the coverage of the 10 2G towers, (b)

maps the coverage of the 38 3G towers (c) maps the coverage of the 7 4G towers and (d) shows the coverage maps of all 55 the cellular towers in the region.

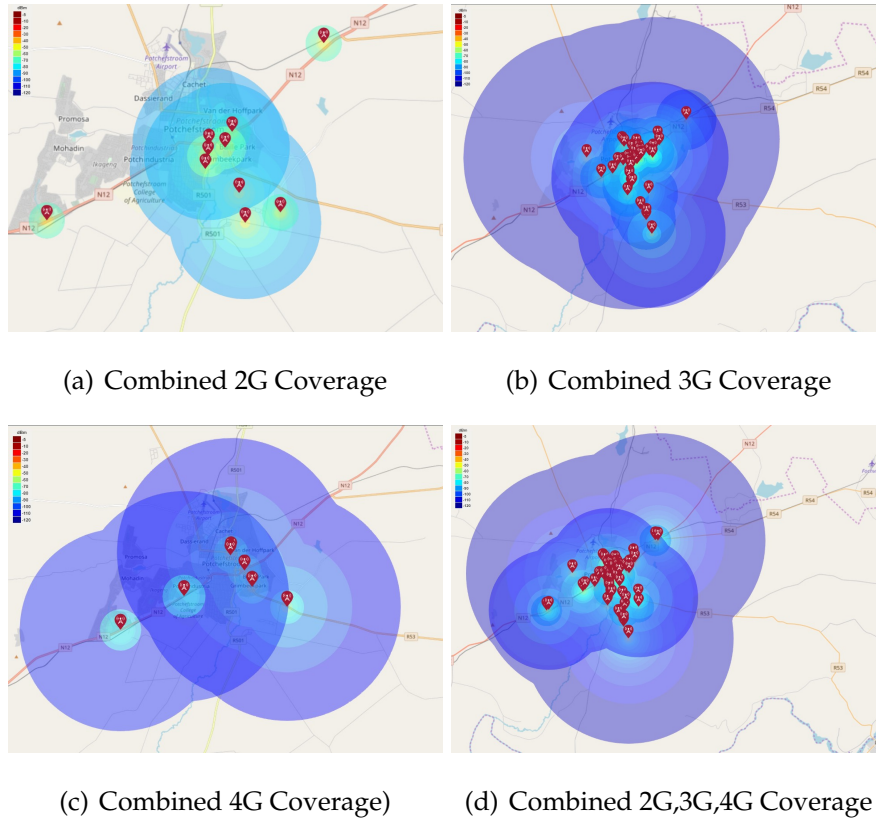


Figure 3.10: Potchefstroom Cellular Coverage of all Combined Providers per Technology Group

It is evident from Figure 3.10, that the coverage of 2G networks is limited and is slowly phasing out and that the 4G network is still emerging in Potchefstroom. Thus the most prominent cellular coverage in Potchefstroom is 3G technology.

3.3.4 Traffic Light Locations

The capacity of IoT devices, which in this case is traffic lights can only be calculated by knowing the typical parameters which were summarised in Table 3.2. The only requirement that still needs to be known is the locations of the traffic lights. This is

essential as the traffic light locations will determine if the cellular network has coverage over these areas and what technology tower should be used for the application depending on the unutilised network space. The GPS location of all 45 traffic lights situated in Potchefstroom was retrieved with Google Maps and Google Earth and was overlaid on a map of Potchefstroom using MATLAB and the mapping toolbox specifically. The Traffic light locations map is shown in Figure 3.11.

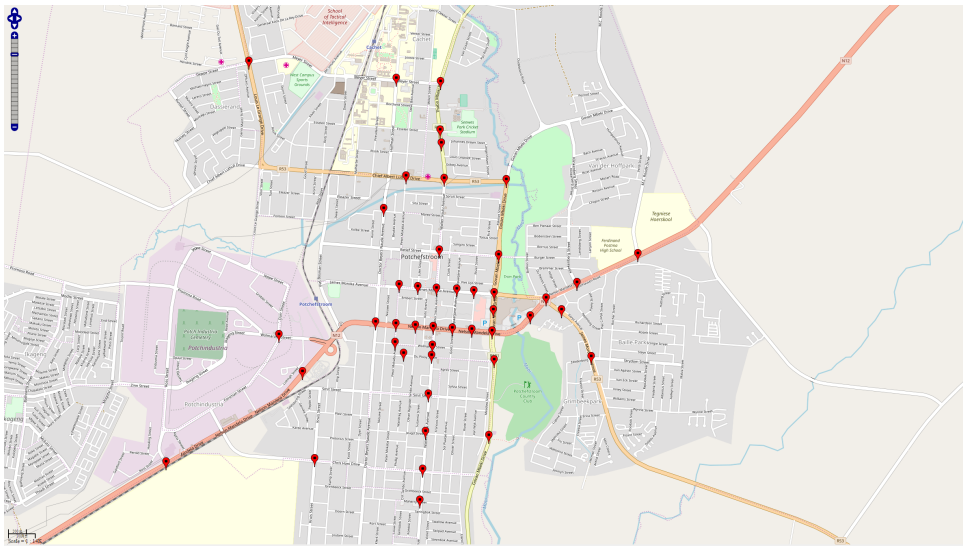


Figure 3.11: IoT traffic light locations

The 45 traffic lights are spread across Potchefstroom and will connect to multiple towers.

3.4 System Model Verification

Verification in the study is done by the researcher to explain to the external reviewers the thought process that was followed on the model that was used. Verification is done by applying strategies to determine the trustworthiness of the model [71]. Firstly a qualitative approach is used to verify the data then a qualitative approach is used to verify the system model.

3.4.1 Verification Methodology

Verification strategies ensure both reliability and validity of the model that is used in this study and the system model it is applied to. The strategies used to verify the system model and data is methodological coherence, sampling sufficiency, developing a dynamic relationship between sampling, data collection and analysis, thinking theoretically, and theory development. These five steps will be implemented to verify the system model. A brief explanation of each is now discussed [71] [72].

- Methodology coherence - This is to ensure the relationship between the research objective and the components of the methods. The quality of the study demands that the objectives match the method, which matches the data used. Each process followed must be verified with the previous process, which in turn verifies the methodology used.
- Sampling sufficiency - This ensures that there is effective saturation in each category of the study, with optimal data quality. Using an adequate amount of data means that sufficient data were obtained for the different phenomenon that can occur in the study.
- Collecting and analysing data - There is a mutual interaction in gathering data in what is known and what needs to be known about the data. Thus data must be understood before it is used. The spacing of data and iterative analysis of the data used is the essence of attaining reliability and validity.
- Thinking theoretically - Ideas from data are transformed into results, and this gives rise to the new ideas. The results that are generated must be verified with the data already gathered. When analysing results continually, checking and rechecking the data builds a solid foundation for the outcome of each generated result.
- Theory development - The development of results is to move between the perspective of the data and the theoretical understanding. The results and literature

of a study are thus developed through two mechanisms, a) As an outcome of a research process. b) A template for comparison and further development.

Following these guidelines and implementing it to the IoT capacity estimation model, verifies the data and the method that was followed. These five strategies should provide evidence of the reliability and validity of the study.

3.4.2 Verification Implementation

The verification of the system model is described systematically by going through Figure 3.1 and applying the verification method described in Section 3.4.1.

Methodology Coherence

The method used in this dissertation is described by the system model diagram in Section 3.2. Each of the system model steps coheres to one another and is of the essence before continuing to the next block. The system model is divided into four main blocks, to cohere to the methodology that is followed in the estimation of IoT capacity. Before any calculations can start in Section A, the city where the model applies to should be specified. Section A consist of various steps and calculations, and it can only be completed if the step before it was completed and verified. By implementing the system model where each step follows on the next, each step also verifies the step before it. In block [1.0] the towers are located, but in [1.1] they are split into the technology generations as each has different specifications and properties. This verifies that there are various towers from multiple carriers in the study area. Each of these towers is plotted in [1.2], which will verify the complete coverage of all the towers in the area as well as a verification that will be used in Section C to ensure coverage over the traffic lights. Blocks [1.3] and [1.4] are used to ensure sufficient sampling that is described in the next process step in the validation, where finally block [1.5] expresses the values of all samples in the correct format which is verified by a lookup on the Erlang B table.

Section B follows almost the same methodology as described for Section A, where the traffic lights are mapped, and the busy hour traffic formulae are used to verify the answers for the minimum and maximum usage of IoT devices on a network. The validation of Section C is done by combining the results from both Section A and B, as the open network spaces that were represented in Erlang is now filled with the minimum and maximum IoT device usage Erlang values. This verifies block [3.1] where an estimated range of devices that can connect to unutilised cellular networks are expressed per technology group with different network utilisation percentages.

By verifying each block with the previous ensures that a methodology coherence verification process is followed during the estimation study.

Sampling Sufficiency

All four leading cellular providers were used to gather data regarding each technology, 2G, 3G and 4G towers to get the best approximation of the signal strengths and capacity of each of the technology in the chosen area of Potchefstroom. By doing this, the verification standard was met by sufficient data sampling as all possible towers in the region was used to determine the average signal strength and cellular capacity in Potchefstroom, assuring the best possible results for this study.

Regarding the traffic intersections, there is only a fixed amount of traffic intersection; thus there is only one set of data. However, in calculating the minimum and maximum requirements for each IoT traffic light, there was a max and min value sampled to have a range of what the need for such devices could be. It was done by replicating the busy hour Erlang calculations, where each IoT device was seen as making calls for a short period of at a time.

By using data from the four leading cellular carriers each with different amount of 2G, 3G and 4G towers each having their own signal strengths an average value for each technology was used to calculate the capacity, thus verifying that sufficient sampling was used in the system model.

Collecting and Analysing Data Concurrently

The data collected regarding the cellular towers was used to plot the coverage of all the cellular network technologies of each network and carrier in the region of IoT implementation to verify the signal strengths and coverage areas.

These average values were used to calculate network capacity for all networks where it was analysed to make sure the devices increase as the network technology progresses, which is added as a verification of the calculated data. With the calculations done it was verified that the number of devices increased as the network technology evolved from 2G to 4G networks.

Traffic light data was collected by looking for all the lights and analysing each intersection, where it is a pedestrian crossing, 3-way intersection or 4-way. This data was analysed in Google maps and verified by actually driving the route where the traffic lights are situated ensuring each intersection position by GPS coordinates. The average value of traffic light time changes was used in calculating the Erlang value for each device the data was analysed and if there are more communication that takes place in the period of an hour, the Erlang value will increase and fewer devices will be able to connect to the cellular network as the load on the network increases.

By analysing the data concurrently with each step of the system model, each calculation and data used is verified by comparison to the previous steps.

Thinking Theoretically

The results from the calculations are seen as new data and are verified by comparing the total IoT devices with the open space of the cellular network. This estimated number for 0 devices on 2G with maximum demand is verified as there is physically no space on the cellular network cell to accommodate an IoT device of such nature, but as soon as the device is used at minimum usage, there is a lot more of IoT devices that can be used. Thus the minimum and maximum value give an estimated range of the

number of IoT devices that can connect on the unutilised space on the cellular network. This is also where the theoretical thinking step of verification comes into play, as most devices specifications are situated in the middle of the range estimated for IoT devices. The theoretical thinking process indicates that an IoT device will never be used at full capacity or its lowest capacity unless it switched off. The results of the capacity estimation are verified by using the method and standard calculation equations.

Theory Development

Various networks types can be used for IoT implementation in Africa; this dissertation focused on a cost-effective way of using current cellular network infrastructure for IoT deployment. This means that only if there is unutilised space on the network, IoT devices can be connected. Thus when considering the theory development from the case study chosen and results in the outcome that is theoretically realised is that it could be possible to use current network infrastructure for the deployment of IoT. These results also create a template and capacity estimations that can be used to compare as new technologies emerge and the current alternate technologies get more cost-effective to implement. This capacity estimation model can be used to compare against the network cost capacity and coverage of LoRa, Sigfox, EC-GSM-IoT, Narrow-Band LTE (NB-LTE) and LTE-M as this way of IoT implementations set the base for African IoT.

3.4.3 Cellular Capacity Verification

As the cellular capacity model is implemented first, it is of utmost importance to verify that the model is correct. The cellular data is gathered from OpenCellid [62] which make use of crowdsourced data and is verified by using another crowdsourced data source NB CellMapper [61] and correlating the eNB (eNodeB) Cell ID. This is the only publicly available data as all cellular providers deem their data as classified.

The split of the data between cellular providers and different generation towers was

achieved by searching the eNB Cell ID in CellMapper thus verifying that the data used for the coverage maps and the signal strengths used is correct.

The application of standard formulae used for cellular capacity calculation from source, [63] verifies that the results of the number of channels per cell are correct. The cellular capacity is verified by the Erlang table which is included in Appendix A.1. The parameters used to verify this is shown in Table 3.4, where after the verified number of channels and the given blocking probability is looked up in the Erlang table to represent the capacity of a single cell of a tower in Erlang showed in Figure 3.12. The single cell result was used to know how many devices every single cell can support before a general tower capacity estimation is given and all the devices lie within a single cell of the tower.

Table 3.4: Cellular Capacity Erlang B Verification

Channels (T)	Blocking Probability	Erlang Capacity
35	2%	26.40E
49	1%	39.30E
99	0.5%	87.00E

Erlang B Table

No. of Channels (N)	Traffic (A) in erlangs for P =																		
	0.1%	0.2%	0.5%	1%	1.2%	1.3%	1.5%	2%	3%	5%	7%	10%	15%	20%	30%	40%	50%		
1	0,001	0,002	0,005	0,010	0,012	0,013	0,02	0,020	0,031	0,053	0,075	0,111	0,176	0,250	0,429	0,667	1,00		
2	0,046	0,065	0,105	0,153	0,168	0,176	0,19	0,223	0,282	0,381	0,470	0,595	0,796	1,00	1,45	2,00	2,73		
3	0,194	0,249	0,349	0,455	0,489	0,505	0,53	0,602	0,715	0,899	1,06	1,27	1,60	1,93	2,63	3,48	4,59		
4	0,439	0,535	0,701	0,869	0,922	0,946	0,99	1,09	1,26	1,52	1,75	2,05	2,50	2,95	3,89	5,02	6,50		
5	0,762	0,900	1,13	1,36	1,43	1,46	1,52	1,66	1,88	2,22	2,50	2,88	3,45	4,01	5,19	6,60	8,44		

Figure 3.12: Erlang B Table Reading Example

There is not a single cellular network that operates at full capacity, thus assuming only a certain percentage of the network capacity is utilised. The unutilised capacity is expressed in Erlang as the final verified result of the model. The used network space is Erlang is determined by multiplying the used percentage, leaving the rest open for IoT device deployment. The methods implemented could verify each step of this part of the system model. The next part can now be implemented.

3.4.4 IoT Erlang Method Verification

From the first generation networks, cellular traffic was determined using the Erlang method. Thus to model the capacity of these older cellular networks, in Africa the Erlang method was used in this study. As 4G still needs to be implemented into the African infrastructure, the Erlang method was also used for 4G networks to ensure a similar result over these three prominent network generations in Africa. Thus to validate why the Erlang method is used for IoT traffic lights, Equation 3.9 is used as a reference point.

$$E = n\lambda t_h \quad (3.9)$$

where: n = number of devices, λ = transmissions/hour and t_h = hours/transmission

The Erlang traffic calculation on a single cellular tower for regular mobile users would be calculated with Equation 3.9. Assume an average number of 1000 calls is made per hour with each call lasting 3 minutes; then applying the equation would result in the Erlang of traffic per hour. Looking at an IoT traffic light and the specifications set in Table 3.2, the amount of data sent is only a few bytes. By using the IoT traffic light specifications, it is noted that a traffic light can change the colour of a light by as quick as 2 seconds. As the Erlang equation calculates the traffic based on an hour time frame, and the light changes every 2 second, leaves 1800 traffic light colour changes in an hour. Thus the maximum number of calls that can be made is 1800 per hour. With the data transmission being only a few bytes, an average time of 25ms per transmission was assumed, thus now having the length of each call. The Erlang model is verified with the fact that the Erlang equation, was used just as if it was regular mobile traffic calculation, but with the number of calls per hour now being 1800 and the call duration 25ms.

To verify that this equation was correctly implemented the Erlang traffic for a single IoT device is calculated by hand and compared to the calculation done in MATLAB with

its percentage error. For this exercise, the parameters in Table 3.5 was used together with Equation 3.10 [64].

Table 3.5: IoT Device Verification Parameters

Number of Devices (n)	Transmissions per hour (λ)	Transmission Time (t_h)
1,20,50	1800	100ms

$$E = n\lambda t_h \quad (3.10)$$

Table 3.6 summarises the result of these two methods of calculation for 1 device compared 20 and 50 devices, which increased the rounding percentage error marginally.

Table 3.6: IoT Erlang Method Verification

Number of Devices	Hand Calculation	MATLAB Calculation	% Rounding Error
1 Device	0.045 Erlang	0.05 Erlang	9% error
20 Device	0.90 Erlang	1.00 Erlang	10% error
50 Device	2.25 Erlang	2.50 Erlang	11.1% error

It is noted that the difference between the two results is very similar, with a percentage Error of 10-11 % which is due to rounding. By rounding up, in the MATLAB calculations ensures that the estimate network capacity required for each device is safely estimated and acts as a precautionary measure to prevent the capacity overload. This verifies that the Erlang method used for IoT device is implemented correctly.

3.4.5 IoT Capacity Estimation Verification

As the cellular capacity, and the required IoT device capacity has been verified, the number of supported IoT devices can be determined.

The parameters used to verify the estimated number of IoT devices is shown in Table 3.7 and from Section 3.4.4 the IoT device capacity requirements are 0.045 Erlang and 0.05 Erlang depending on calculation method.

Table 3.7: IoT Estimation Verification Parameters

Parameter	2G	3G	4G
Cluster size(K)	7	7	4
Channels(T)	35	49	56
Channels per cell(N)	5	7	14
Blocking Probability	2%	2%	2%
Erlang B Table	1.657E	2.935E	8.200E

Equation 3.11 is applied to estimate the number of IoT devices.

$$EstimateDevices = \frac{CellularCapacity(inErlang)}{DeviceCapacityRequirement(inErlang)} \quad (3.11)$$

The values in Table 3.8 summarise the verification Equation 3.11 and results achieved with the percentage error calculated between the Matlab and hand calculate IoT requirement value.

Table 3.8: IoT Capacity Estimation Verification

Cellular Capacity	IoT Matlab Requirement	IoT Hand Requirement	Hand Device Estimate	Matlab Device Estimate	% error Devices
1.657E	0.05E	0.045E	33	36	8.33%
2.935E	0.05E	0.045E	58	65	10.77%
8.200E	0.05E	0.045E	164	182	9.89%

It should be noted that since the Erlang number is only an estimate, the values obtained from Equation 3.11 should be treated as an estimate and not absolute values. The

percentage error shows that there is an average of 10% overhead in the calculations due to rounding.

3.5 Concluding Remarks

With the system model describing how the study is conducted, each section of the model was implemented. The cellular capacity is calculated for each technology generation, and the traffic lights data transmission intervals are used to determine capacity requirements for an IoT device. The coverage maps of Potchefstroom was plotted in MATLAB with the Mapping toolbox as well as the traffic lights. Lastly, the system model and data are verified by implementing the five steps and system verifications described in Section 3.4. It is clear that with each method implemented the data used, and the system model could be verified.

Chapter 4

Results and Validation

In this chapter, the results are discussed in the order of the system model implementation. The results include the cellular capacity, IoT traffic light and IoT capacity estimation results. Before the chapter conclusion, the results obtained are validated by the validation methodology.

4.1 Cellular Capacity Results

Approaching the IoT capacity estimation with the Erlang traffic method, the results for 2G, 3G and 4G networks are tabulated in Table 4.1. The number of channels used was an average obtained from various cellular calculations in the model implementation. The average blocking probability during busy hours in a cellular system is 1-2%. A worst-case scenario was used in these calculations, and the Erlang capacity values of 0.5%, 1% and 2% blocking probability were used and read from the Erlang B table. The calculations were done for each of the different network generations.

Table 4.1, shows that if the specifications are kept as the standard for each network generation and the blocking probability decreases, the Erlang value associated with the

Table 4.1: 2G, 3G, 4G Cellular Capacity Results

Parameter	2G	3G	4G
C/I	15dB	14dB	13dB
Co-channel reuse ratio (d/r)	3.7114	Cellular	Cellular
Cluster size(K)	7	7	4
Channels(T)	35	49	56
Channels per cell(N)	5	7	14
Number of clusters(M)	3	3	3
Erlang B table(2%) per cell	1.657E	2.935E	8.200E
Erlang B table(1%) per cell	1.361E	2.501E	7.352E
Erlang B table(0.5%) per cell	1.132E	2.158E	6.663E

blocking probability and number of channels per cell also decreases. This is verified and validated by using the calculated value of channels per cell (N) and looking up the Erlang value in the Erlang B table in Appendix A.1.

4.2 IoT Traffic Light Results

The Erlang traffic calculations were done with the specifications provided in Table 3.2, although the maximum transmission interval is 120s, according to Equation 3.8 the average transmission time should be used. The average transmission value used was thus, 61s and was used as the maximum transmission interval. The minimum transmission interval used was 2s as was provided by the specifications in Table 3.2. A result of the Erlang requirements for a single IoT traffic light is shown in Table 4.2, as well as the network capacity required in Erlang to support 20 and 50 devices. This gives an

estimate Erlang range of the requirement for a single IoT device. This is necessary to determine an estimate of IoT devices that can work on an African cellular tower.

Table 4.2: IoT device Erlang Requirements

Interval	1 Device	20 Devices	50 Devices
Tx Interval 61s	0.0016E	0.0328E	0.0820E
Tx Interval 2s	0.0500E	1.0000E	2.5000E

4.3 IoT Capacity Estimation Results

Knowing the Erlang capacity of the cellular network, the number of IoT devices that could fit in the capacity of the cellular network had to be calculated. In Table 4.3, Table 4.4 and Table 4.5 calculations were done with the probability that the cellular network mobile users was 80%, 90%, 95% and 98% respectively and the remaining network space was unused network capacity that could be utilised for IoT device connectivity. Using the Erlang requirements for an IoT device, the calculations were done for the minimum and maximum IoT devices that could be supported on a single 2G, 3G and 4G cellular tower cell. These results are given per cell as each cell that makes up a cellular tower can only support a specific number of devices and knowing that the capacity each cell can handle will identify if there are too many IoT devices within a cells capacity to handle. If the coverage of the cells like in this case study covers the number of traffic lights the answer can be multiplied to determine the estimated cellular tower coverage. The capacity results are now discussed and presented per cell for each given scenario.

4.3.1 2% Erlang Blocking Probability

The results from applying the 2% blocking probability with the Erlang B table had the following estimate of IoT devices, summarised in Table 4.3.

Table 4.3: IoT capacity estimation results per cell with a 2% Erlang blocking probability

Available Erlang	Network Users(%)	IoT Usage(%)	Min IoT Devices	Max IoT Devices
2G				
1.657E	98%	2%	0	20
	95%	5%	1	51
	90%	10%	3	103
	80%	20%	6	207
3G				
2.935E	98%	2%	1	36
	95%	5%	2	91
	90%	10%	5	183
	80%	20%	11	366
4G				
8.200E	98%	2%	3	102
	95%	5%	8	256
	90%	10%	16	512
	80%	20%	32	1025

The IoT capacity estimation results for a 2% blocking probability in Table 4.3 indicates that for a 2G cellular network the minimum and maximum IoT devices are 0 and 207 respectively for this specific network setup. It is possible for the minimum devices to be zero as Potchefstroom has limited 2G coverage and the worst-case IoT device specification was used, showing that the network cannot handle this type of IoT device. Considering a 3G cellular network, the minimum and maximum IoT devices are 1 and 366 respectively. Finally, a 4G cellular network can support the most devices in Potchefstroom, with an estimated minimum of 3 devices, and a maximum of 1025 devices per single cell in a cluster.

4.3.2 1% Erlang Blocking Probability

The results from applying the 1% blocking probability with the Erlang B table had the following estimate of IoT devices, summarised in Table 4.4.

For a 1% blocking probability, the results in Table 4.4 shows that for a 2G cellular network the minimum and maximum IoT devices are 0 and 170 respectively. Once again

Table 4.4: IoT capacity estimation results per cell with a 1% Erlang blocking probability

Available Erlang	Network Users(%)	IoT Usage(%)	Min IoT Devices	Max IoT Devices
2G				
1.361E	98%	2%	0	17
	95%	5%	1	42
	90%	10%	2	85
	80%	20%	5	170
3G				
2.501E	98%	2%	1	31
	95%	5%	2	78
	90%	10%	5	156
	80%	20%	10	312
4G				
7.352E	98%	2%	2	91
	95%	5%	7	229
	90%	10%	14	459
	80%	20%	29	919

the minimum device is zero and indicates that 2G cellular networks do not support the requirements of this IoT device. Considering the 3G cellular network, the minimum and maximum IoT devices are 1 and 312 respectively. Finally, a 4G cellular network can support the most devices, with an estimated minimum of 2 devices, and a maximum of 919 devices per single cell in a cluster.

4.3.3 0.5% Erlang Blocking Probability

The results from applying the 0.5% blocking probability with the Erlang B table had the following estimate of IoT devices, summarised in Table 4.5.

The IoT capacity estimation results for a 0.5% blocking probability in Table 4.5 shows that for a 2G cellular network the minimum and maximum IoT devices are 0 and 141 respectively for this type of network setup. The 3G cellular network can support a minimum and maximum of 0 and 269 IoT devices respectively. Lastly, the 4G cellular network can support the most devices, with an estimated minimum of 2 devices, and a maximum of 832 devices per single cell in a cluster.

Table 4.5: IoT capacity estimation results per cell with a 0.5% Erlang blocking probability

Available Erlangs	Network Users(%)	IoT Usage(%)	Min IoT Devices	Max IoT Devices
2G				
1.132E	98%	2%	0	14
	95%	5%	1	35
	90%	10%	2	70
	80%	20%	4	141
3G				
2.158E	98%	2%	0	26
	95%	5%	2	67
	90%	10%	4	134
	80%	20%	8	269
4G				
6.663E	98%	2%	2	83
	95%	5%	6	208
	90%	10%	13	416
	80%	20%	26	832

In Table 4.3 and Table 4.5, it is seen that the number of devices from the 0.5% blocking probability is higher than that of the 2% blocking probability. This is because although the blocking probability was changed the values of $\frac{C}{T}$, K and T remained the same. This was done as a comparison point with the same data values read from the Erlang table, and it is clear that the network blocking probability also has a design aspect that contribute to the values of $\frac{C}{T}$, K and T . The main focus however was to estimate the number of IoT device in a single cell with a blocking probability of 2% and compare it with other blocking probabilities.

4.4 Results Validation

A great deal of attention is applied to the validation, therefore validating the results contributes to the reliability and trustworthiness of the study [71].

4.4.1 Validation Methodology

All research must have a truth value, applicability and consistency for the study to be worthwhile. To ensure the capacity estimation study adheres to these values, validation on the results is implemented [71]. There are various methods used to validate research depending on the topic. This dissertation uses standards and literature as validation methods.

- **Standards** - Standards are a comprehensive approach to measure research as a whole. This is because standards are represented either as the minimally acceptable level or a gold standard which is practically impossible to reach. Thus having a broad field of correctness and splits the ideal and the real results with an acceptable margin of correctness. Using standards to validate research is a judgement of the relative worth of the research applied to the completion of the study results [71].
- **Literature** - Using the literature that leads up to the research is a method used to validate that the estimation study could solve a problem identified in the literature. By using the literature combined with standards, validates that the research conducted could solve the problem and that the outcome is worthwhile.

4.4.2 Validation Implementation

With the verification process conducted on the system model, the validation must be conducted by following the validation method suggested. The results will be validated by using standards and literature in the following subsections.

Validation of Erlang Method for IoT devices

Referring to Section 2.2.2, it was noted that in 2014 and 2017, 2G and 3G cellular networks was the most prominent networks in Africa with the 4G network being imple-

mented. In 2023, it is predicted that 2G and 3G networks will still make up 50% of the African cellular network. Thus most IoT implementations would be implemented on 2G and 3G cellular network. These networks traffic models do not include the use of IP addresses for each device as in 4G networks. The standards used for the smart traffic lights, research was done on the minimum, and maximum time it takes for traffic lights to change colour, and the standard equation that is used for cellular traffic was used for IoT device capacity requirements. This equation for IoT device was verified in Section 3.4.4. Thus by applying the same method and equation used for regular cellular capacity calculation validates that the method is also valid for the IoT device requirements.

Validation of IoT Capacity Results

As stated in Section 2.2, there are various standards in the cellular network environment, which one of the leading players in this field is the 3GPP. As this study stretches to include the whole of Africa the standards used in this study and validation is based on the 3GPP releases. These 3GPP releases for this study were interpreted that 4G networks are better and faster than 3G, 3G networks are faster than 2G, and 2G networks are better and more advanced than 1G networks. Some fundamental values used in conjunction with the crowdsourced data can be found in Section 3.2.1 with the methodology followed. Using standard cellular capacity calculations and formulae together with the values in Table 4.6, for 2G, 3G and 4G cellular network towers, In Table 4.7 compares the average number of devices with the calculated estimate IoT device capacity.

In Table 4.7, the standard network specifications that were used indicates the capacity of a cellular network for each technology generation. The average capacity was calculated using the values from Table 4.6 thus the values used were a cluster size of 3 for all three technologies, with the number of channels per cluster cell being 35, 49 and 99 respectively for 2G, 3G and 4G networks. The Erlang capacity was read from the Erlang B table with the average of a 2% blocking probability. According to [73], the

average usage per user in a cellular network is 0.005 Erlang. Thus by filling up the Erlang value per tower, the capacity was calculated and compared to the capacity of the network should be utilised with IoT devices. Thus even utilising the cellular network tower for IoT devices only, each generation technology has valid capacity values.

Table 4.6: Validation Average Parameters

Parameter	2G	3G	4G
Cluster size(K)	3	3	3
Channels(T)	35	49	99
Erlang B table(2%) per cell	6.61E	9.83E	24.60E
1 IoT Device Capacity	0.005E	0.005E	0.005E

Table 4.7: Validation by 3GPP Standards and Specifications

Network type	Average Capacity (users per Cell)	Calculated Capacity (devices per Cell)	% Deviation	Acceptable
2G	1322	1035	21.7%	Validated
3G	1966	1834	6.7%	Validated
4G	4920	5125	4.2%	Validated

The % deviations of the 3G and 4G networks are acceptable as it is less than 10%, although the 4G estimation overshoots the average capacity. The 2G networks % deviation, on the other hand, is a significant 21.7%. This, however, does not overshoot the average capacity which ensures that there is network space for IoT devices with higher specifications. The calculated value is just an estimate value which is compared with an average value.

It is noted in the 4G results that the IoT calculation value overshoots the standard average capacity. The overshoot is not significant, being only 4.2%. The reason for this could be as 2G, and 3G networks use circuit switching compared to 4G networks that

use packet switching. Thus by applying the Erlang method to 4G networks could result in with an overshoot value, because a circuit switching Erlang method is used. This method was used to have one standard when comparing these three different networks. As 4G networks, currently only make up 8% of the African cellular network compared to the widespread 2G and 3G networks the Erlang method was preferred. The 4G results are still valid as the calculated capacity utilises the complete cellular network with IoT devices and in the case of the device, it is never used at its full potential.

Validation of Research

To validate the research done by literature and ensuring that the solution can be applied to the case study, this section will refer to the literature study. As stated in Section 2.1.4, and Table 2.8, SSA is the least ready to implement IoT, but that specific study did not include cellular networks. Thus including cellular networks into this dissertation as a network for IoT deems to be a solution for IoT in an African context. The cellular infrastructure in SSA is underdeveloped when compared to the rest of the world as illustrated in Figure 2.6 and Figure 2.7 from Section 2.2.2. In 2014 the main cellular networks used was 2G and 3G. By 2022 it is predicted that more than 47% of cellular networks in Africa would be mostly 2G and 3G networks and 42% 4G. This validates that the reason for 2G, 3G and 4G as the primary deployment networks for IoT in Africa is valid.

The case study identified for the capacity estimation of IoT devices on a cellular network is a study done by KPMG as described in Section 2.1.5. Traffic congestion is a significant problem in South Africa; thus by looking into IoT traffic lights, the case study is valid by possibly introducing a solution to the traffic congestion problem without having the significant cost of road construction.

4.5 Concluding Remarks

This chapter presented the results of the study and the validation thereof. The result of the cellular capacity showed that as the blocking probability increased when using the standard cellular specifications set for this study, the network capacity Erlang value decreased. This resulted in less space for IoT devices on the cellular network. As the Erlang B table was used to achieve these Erlang values, this phenomenon is verified and validated. From the coverage maps of Potchefstroom, the most prominent network was the 3G network with 38 towers. Thus the number of towers times the devices will deliver the highest range of IoT devices. As there are only 45 traffic lights, the network will be more than capable of implementing IoT connected traffic lights, and further applications can now be studied. The study is validated by using standards and literature which concluded the results to be valid. The next chapter will focus on the final concluding remarks and proposed recommendations for future work.

Chapter 5

Conclusion and Recommendations

This chapter summarises the work that was done and the research goals that were set out. Suggestions and recommendations are discussed for future work on this research topic followed by the concluding remarks of the dissertation.

5.1 Summary of work done

Looking at the work done in this dissertation the flow of the system model is followed. The chosen city used is Potchefstroom as the data needed was easily accessible. Using cellular data from 2G, 3G and 4G technologies from 4 service providers a good base of coverage of Potchefstroom were mapped in MATLAB to ensure full coverage for the IoT scenario chosen. The KPMG study discussed in Section 2.1.5, lead the scenario to traffic management and smart traffic lights was used as the case study for IoT devices. Each intersection with traffic lights in Potchefstroom was mapped and using the coverage maps of the traffic lights was covered by a form of cellular technology. Assuming different blocking probabilities, the cellular tower capacity was expressed as an Erlang value. The traffic light specification was used, and an Erlang value range

was determined for a single IoT traffic light by using basic cellular traffic calculations. Assuming that the cellular networks were not fully occupied by cellular users the remaining space was filled with the Erlang value of a single IoT device which in turn resulted in an estimated range of IoT devices that can utilise the open spaces on cellular towers.

It was found that it is possible to use the existing cellular infrastructure in Africa for IoT implementations. The maximum estimation of IoT devices for 2G networks was 207 devices, for 3G 366 devices and lastly for 4G 1025 devices. With only 45 traffic lights and the 3G network being the most prominent with 38 towers, the number of towers multiplied by the number of devices will deliver the highest range of IoT devices for Potchefstroom.

5.2 Recommendations for future work

Regarding future work for IoT capacity estimation in Africa, three main suggestions are advised. Firstly with the rise of 5G networks, it would be interesting to see how 5G compare to the previous generation technologies. This, however, was not included in this dissertation as 5G is not yet widely deployed commercially. Secondly, other network technologies are looked into in this study but not necessary approached with a capacity estimation for IoT devices. It would thus make an excellent study to compare all these IoT network technologies mentioned in the literature study. A comparison of IoT capacity, network infrastructure and the cost to install and operate each network would give more insight in which network is the most optimised for IoT. Lastly, with a model to estimate the capacity of IoT devices on an African mobile network, future work that can be considered is to build a model for the capacity of various IoT devices with a range of different applications. The capacity of IoT devices could vary significantly if other applications are considered.

5.3 Research Goals

The research goals and objectives were set out in Section 1.3, these objectives was a) to identify a network in Africa for IoT deployment, (b) identify a scenario where IoT can be implemented in a city, (c) estimate the capacity of the chosen network and (d) estimate IoT devices that can be supported with the existing cellular network.

5.4 Conclusion

Internet of Things is leading the world into smart, safe and connected cities where machines can communicate with each other seamlessly through wireless technologies. First world countries would benefit from these technologies long before developing countries, as they are still in need of infrastructure to support such a large number of devices. By researching possible networks for IoT deployment in Africa, it was found that from LoRa, Sigfox, EC-GSM-IoT, NB-IoT and LTE-M, the best option was to use existing cellular infrastructure due to the financial implication involved in deploying a new network for IoT.

This dissertation determined the estimated number of IoT devices that can be connected to an African Cellular Network. By using the Erlang approach, the capacity calculation method was tested on Potchefstroom data as a case study and showed promising results. This method would be deemed sufficient to calculate the estimated capacity and determine if it is possible to connect smart IoT traffic lights in African cities current cellular infrastructure.

Compared to the related work which focuses on LTE and LTE-M networks for IoT, the method for the use case of Potchefstroom showed that 3G networks have more coverage than 4G networks. With the number of 3G towers and IoT capacity estimation, 3G networks provide the best solution for Potchefstroom. The method used can be applied to any African city, and the results would determine which network generation

would be sufficient to implement IoT traffic light devices, and the estimate amount devices for that city's use case. The results of the capacity estimation verify that the existing network can accommodate the load of this implementation.

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Appendix A

Appendix

The Appendix consists of two Sections; the Erlang B table is included in Section A.1. It was used for the cellular traffic calculations reading off the number of channels in a cell and the blocking probability used. This, in turn, results in an Erlang value which is used for further cellular traffic calculations.

Section A.2 contains the accepted conference paper that was presented at the IEEE Global Conference on Internet of Things in Alexandria, Egypt 5-7 December 2018.

A.1 Erlang B table

Erlang B Traffic Table

N/B	Maximum Offered Load Versus B and N											
	B is in %											
	0.01	0.05	0.1	0.5	1.0	2	5	10	15	20	30	40
1	.0001	.0005	.0010	.0050	.0101	.0204	.0526	.1111	.1765	.2500	.4286	.6667
2	.0142	.0321	.0458	.1054	.1526	.2235	.3813	.5954	.7962	1.000	1.449	2.000
3	.0868	.1517	.1938	.3490	.4555	.6022	.8994	1.271	1.603	1.930	2.633	3.480
4	.2347	.3624	.4393	.7012	.8694	1.092	1.525	2.045	2.501	2.945	3.891	5.021
5	.4520	.6486	.7621	1.132	1.361	1.657	2.219	2.881	3.454	4.010	5.189	6.596
6	.7282	.9957	1.146	1.622	1.909	2.276	2.960	3.758	4.445	5.109	6.514	8.191
7	1.054	1.392	1.579	2.158	2.501	2.935	3.738	4.666	5.461	6.230	7.856	9.800
8	1.422	1.830	2.051	2.730	3.128	3.627	4.543	5.597	6.498	7.369	9.213	11.42
9	1.826	2.302	2.558	3.333	3.783	4.345	5.370	6.546	7.551	8.522	10.58	13.05
10	2.260	2.803	3.092	3.961	4.461	5.084	6.216	7.511	8.616	9.685	11.95	14.68
11	2.722	3.329	3.651	4.610	5.160	5.842	7.076	8.487	9.691	10.86	13.33	16.31
12	3.207	3.878	4.231	5.279	5.876	6.615	7.950	9.474	10.78	12.04	14.72	17.95
13	3.713	4.447	4.831	5.964	6.607	7.402	8.835	10.47	11.87	13.22	16.11	19.60
14	4.239	5.032	5.446	6.663	7.352	8.200	9.730	11.47	12.97	14.41	17.50	21.24
15	4.781	5.634	6.077	7.376	8.108	9.010	10.63	12.48	14.07	15.61	18.90	22.89
16	5.339	6.250	6.722	8.100	8.875	9.828	11.54	13.50	15.18	16.81	20.30	24.54
17	5.911	6.878	7.378	8.834	9.652	10.66	12.46	14.52	16.29	18.01	21.70	26.19
18	6.496	7.519	8.046	9.578	10.44	11.49	13.39	15.55	17.41	19.22	23.10	27.84
19	7.093	8.170	8.724	10.33	11.23	12.33	14.32	16.58	18.53	20.42	24.51	29.50
20	7.701	8.831	9.412	11.09	12.03	13.18	15.25	17.61	19.65	21.64	25.92	31.15
21	8.319	9.501	10.11	11.86	12.84	14.04	16.19	18.65	20.77	22.85	27.33	32.81
22	8.946	10.18	10.81	12.64	13.65	14.90	17.13	19.69	21.90	24.06	28.74	34.46
23	9.583	10.87	11.52	13.42	14.47	15.76	18.08	20.74	23.03	25.28	30.15	36.12
24	10.23	11.56	12.24	14.20	15.30	16.63	19.03	21.78	24.16	26.50	31.56	37.78
25	10.88	12.26	12.97	15.00	16.13	17.51	19.99	22.83	25.30	27.72	32.97	39.44
26	11.54	12.97	13.70	15.80	16.96	18.38	20.94	23.89	26.43	28.94	34.39	41.10
27	12.21	13.69	14.44	16.60	17.80	19.27	21.90	24.94	27.57	30.16	35.80	42.76
28	12.88	14.41	15.18	17.41	18.64	20.15	22.87	26.00	28.71	31.39	37.21	44.41
29	13.56	15.13	15.93	18.22	19.49	21.04	23.83	27.05	29.85	32.61	38.63	46.07
30	14.25	15.86	16.68	19.03	20.34	21.93	24.80	28.11	31.00	33.84	40.05	47.74
31	14.94	16.60	17.44	19.85	21.19	22.83	25.77	29.17	32.14	35.07	41.46	49.40
32	15.63	17.34	18.21	20.68	22.05	23.73	26.75	30.24	33.28	36.30	42.88	51.06
33	16.34	18.09	18.97	21.51	22.91	24.63	27.72	31.30	34.43	37.52	44.30	52.72
34	17.04	18.84	19.74	22.34	23.77	25.53	28.70	32.37	35.58	38.75	45.72	54.38
35	17.75	19.59	20.52	23.17	24.64	26.44	29.68	33.43	36.72	39.99	47.14	56.04
36	18.47	20.35	21.30	24.01	25.51	27.34	30.66	34.50	37.87	41.22	48.56	57.70
37	19.19	21.11	22.08	24.85	26.38	28.25	31.64	35.57	39.02	42.45	49.98	59.37
38	19.91	21.87	22.86	25.69	27.25	29.17	32.62	36.64	40.17	43.68	51.40	61.03
39	20.64	22.64	23.65	26.53	28.13	30.08	33.61	37.72	41.32	44.91	52.82	62.69
40	21.37	23.41	24.44	27.38	29.01	31.00	34.60	38.79	42.48	46.15	54.24	64.35
41	22.11	24.19	25.24	28.23	29.89	31.92	35.58	39.86	43.63	47.38	55.66	66.02
42	22.85	24.97	26.04	29.09	30.77	32.84	36.57	40.94	44.78	48.62	57.08	67.68
43	23.59	25.75	26.84	29.94	31.66	33.76	37.57	42.01	45.94	49.85	58.50	69.34

44	24.33	26.53	27.64	30.80	32.54	34.68	38.56	43.09	47.09	51.09	59.92	71.01
45	25.08	27.32	28.45	31.66	33.43	35.61	39.55	44.17	48.25	52.32	61.35	72.67
46	25.83	28.11	29.26	32.52	34.32	36.53	40.55	45.24	49.40	53.56	62.77	74.33
47	26.59	28.90	30.07	33.38	35.22	37.46	41.54	46.32	50.56	54.80	64.19	76.00
48	27.34	29.70	30.88	34.25	36.11	38.39	42.54	47.40	51.71	56.03	65.61	77.66
49	28.10	30.49	31.69	35.11	37.00	39.32	43.53	48.48	52.87	57.27	67.04	79.32
50	28.87	31.29	32.51	35.98	37.90	40.26	44.53	49.56	54.03	58.51	68.46	80.99
51	29.63	32.09	33.33	36.85	38.80	41.19	45.53	50.64	55.19	59.75	69.88	82.65
52	30.40	32.90	34.15	37.72	39.70	42.12	46.53	51.73	56.35	60.99	71.31	84.32
53	31.17	33.70	34.98	38.60	40.60	43.06	47.53	52.81	57.50	62.22	72.73	85.98
54	31.94	34.51	35.80	39.47	41.51	44.00	48.54	53.89	58.66	63.46	74.15	87.65
55	32.72	35.32	36.63	40.35	42.41	44.94	49.54	54.98	59.82	64.70	75.58	89.31
56	33.49	36.13	37.46	41.23	43.32	45.88	50.54	56.06	60.98	65.94	77.00	90.97
57	34.27	36.95	38.29	42.11	44.22	46.82	51.55	57.14	62.14	67.18	78.43	92.64
58	35.05	37.76	39.12	42.99	45.13	47.76	52.55	58.23	63.31	68.42	79.85	94.30
59	35.84	38.58	39.96	43.87	46.04	48.70	53.56	59.32	64.47	69.66	81.27	95.97
60	36.62	39.40	40.80	44.76	46.95	49.64	54.57	60.40	65.63	70.90	82.70	97.63
61	37.41	40.22	41.63	45.64	47.86	50.59	55.57	61.49	66.79	72.14	84.12	99.30
62	38.20	41.05	42.47	46.53	48.77	51.53	56.58	62.58	67.95	73.38	85.55	101.0
63	38.99	41.87	43.31	47.42	49.69	52.48	57.59	63.66	69.11	74.63	86.97	102.6
64	39.78	42.70	44.16	48.31	50.60	53.43	58.60	64.75	70.28	75.87	88.40	104.3
65	40.58	43.52	45.00	49.20	51.52	54.38	59.61	65.84	71.44	77.11	89.82	106.0
66	41.38	44.35	45.85	50.09	52.44	55.33	60.62	66.93	72.60	78.35	91.25	107.6
67	42.17	45.18	46.69	50.98	53.35	56.28	61.63	68.02	73.77	79.59	92.67	109.3
68	42.97	46.02	47.54	51.87	54.27	57.23	62.64	69.11	74.93	80.83	94.10	111.0
69	43.77	46.85	48.39	52.77	55.19	58.18	63.65	70.20	76.09	82.08	95.52	112.6
70	44.58	47.68	49.24	53.66	56.11	59.13	64.67	71.29	77.26	83.32	96.95	114.3
71	45.38	48.52	50.09	54.56	57.03	60.08	65.68	72.38	78.42	84.56	98.37	116.0
72	46.19	49.36	50.94	55.46	57.96	61.04	66.69	73.47	79.59	85.80	99.80	117.6
73	47.00	50.20	51.80	56.35	58.88	61.99	67.71	74.56	80.75	87.05	101.2	119.3
74	47.81	51.04	52.65	57.25	59.80	62.95	68.72	75.65	81.92	88.29	102.7	120.9
75	48.62	51.88	53.51	58.15	60.73	63.90	69.74	76.74	83.08	89.53	104.1	122.6
76	49.43	52.72	54.37	59.05	61.65	64.86	70.75	77.83	84.25	90.78	105.5	124.3
77	50.24	53.56	55.23	59.96	62.58	65.81	71.77	78.93	85.41	92.02	106.9	125.9
78	51.05	54.41	56.09	60.86	63.51	66.77	72.79	80.02	86.58	93.26	108.4	127.6
79	51.87	55.25	56.95	61.76	64.43	67.73	73.80	81.11	87.74	94.51	109.8	129.3
80	52.69	56.10	57.81	62.67	65.36	68.69	74.82	82.20	88.91	95.75	111.2	130.9
81	53.51	56.95	58.67	63.57	66.29	69.65	75.84	83.30	90.08	96.99	112.6	132.6
82	54.33	57.80	59.54	64.48	67.22	70.61	76.86	84.39	91.24	98.24	114.1	134.3
83	55.15	58.65	60.40	65.39	68.15	71.57	77.87	85.48	92.41	99.48	115.5	135.9
84	55.97	59.50	61.27	66.29	69.08	72.53	78.89	86.58	93.58	100.7	116.9	137.6
85	56.79	60.35	62.14	67.20	70.02	73.49	79.91	87.67	94.74	102.0	118.3	139.3
86	57.62	61.21	63.00	68.11	70.95	74.45	80.93	88.77	95.91	103.2	119.8	140.9
87	58.44	62.06	63.87	69.02	71.88	75.42	81.95	89.86	97.08	104.5	121.2	142.6
88	59.27	62.92	64.74	69.93	72.82	76.38	82.97	90.96	98.25	105.7	122.6	144.3
89	60.10	63.77	65.61	70.84	73.75	77.34	83.99	92.05	99.41	107.0	124.0	145.9
90	60.92	64.63	66.48	71.76	74.68	78.31	85.01	93.15	100.6	108.2	125.5	147.6

91	61.75	65.49	67.36	72.67	75.62	79.27	86.04	94.24	101.8	109.4	126.9	149.3
92	62.58	66.35	68.23	73.58	76.56	80.24	87.06	95.34	102.9	110.7	128.3	150.9
93	63.42	67.21	69.10	74.50	77.49	81.20	88.08	96.43	104.1	111.9	129.8	152.6
94	64.25	68.07	69.98	75.41	78.43	82.17	89.10	97.53	105.3	113.2	131.2	154.3
95	65.08	68.93	70.85	76.33	79.37	83.13	90.12	98.63	106.4	114.4	132.6	155.9
96	65.92	69.79	71.73	77.24	80.31	84.10	91.15	99.72	107.6	115.7	134.0	157.6
97	66.75	70.65	72.61	78.16	81.25	85.07	92.17	100.8	108.8	116.9	135.5	159.3
98	67.59	71.52	73.48	79.07	82.18	86.04	93.19	101.9	109.9	118.2	136.9	160.9
99	68.43	72.38	74.36	79.99	83.12	87.00	94.22	103.0	111.1	119.4	138.3	162.6
100	69.27	7~.25	75.24	80.91	84.06	87.97	95.24	104.1	112.3	120.6	139.7	164.3

N is the number of servers. The numerical column headings indicate blocking probability B in %. Table generated by Dan Dexter

A.2 IEEE GCloT Paper

Cellular IoT Capacity Estimation for African Smart Cities

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Abstract—Improvements in Internet of Things (IoT) enabling technology lead to increased potential for creating smart and safe cities for the future. While many first world countries already reap the benefits of this technology, developing countries, specifically those in Sub-Saharan Africa, still need to overcome significant barriers before experiencing the same value. Two of these barriers are a) existing network infrastructure and b) limited financial backing to implement a stand-alone IoT network. In most African cities repeated and extensive cable theft lead to the degradation of the fixed line infrastructure to such an extent that operators are reluctant to replace copper or fibre cables. The uptake of wireless technology, however, increased significantly. While cellular communication technology is prevalent in Africa, it should be noted that in most towns and cities this means a third-generation (3G) or earlier implementation. If an IoT deployment were to be considered for this environment, this should be taken into account. In this paper, a capacity estimation is performed for a typical town in South Africa, using the existing cellular technology as an input parameter. As a small initial step towards the creation of a smart city, the case of using IoT technology for traffic light management is considered in a simulation environment. The results of the simulation verify that the current network can accommodate the load of this implementation and the maximum number of devices that can communicate using the current infrastructure is calculated.

Index Terms—African IoT, Capacity Estimation, Cellular Networks, Internet of Things, Safe City, Smart City

I. INTRODUCTION

The concept of IoT (Internet of Things) is one of the most pursued research topics since 2009, and it is the future of M2M (Machine-to-machine) communication [1]. IoT devices can be categorised but are not limited to the following: Consumer Electronics, Security and Public Safety, Automotive, Utilities, Remote Maintenance, Payment and Health. In 2017, analyst firm Gartner estimated that in 2020 there would be 20.4 billion IoT devices connected (excluding smartphones, tablets, and computers) [2].

The formal ITU (International Telecommunication Union) definition of IoT is "A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies" [3]. IoT technology can be deployed in various ways, but for this paper, an IoT deployment is defined as: "An electronic device (sensor, mobile, pc, etc.) that is connected to the internet via any network (fibre, cellular, etc.) gathering valuable information regarding the field where the IoT device is deployed".

The most typical IoT applications to create safe and smart cities requires long-range networks. Common networks used for IoT devices are LoRaWAN, Sigfox, NB-IoT, LTE-M and general GSM networks (2G, 3G, 4G), depending on the IoT device application [1], [4], [5].

For IoT deployments in Africa the network requirements cannot always be met, or when they are met, availability may not be reliable. A study regarding the readiness of IoT deployment in various parts of the world found Sub-Saharan Africa to be the least ready for IoT deployment. The study, however, didn't consider the possibility of using cellular network infrastructure to realise IoT deployments [6].

The cellular growth in Sub-Saharan Africa is expected to be of the highest growing cellular networks in the next four years [7]. The prevalence of cellular technology in Sub-Saharan Africa, therefore, makes it worth-while to consider the possibility of implementing IoT in this scenario. In this paper, the capacity of existing cellular infrastructure to accommodate IoT devices will be investigated.

A study conducted in KPMG in 2017 stated that a significant amount of time which could have been spent on something more productive is lost as a result of traffic congestion [8]. Hence, the IoT deployment considered in this paper will be smart connected traffic lights with the aim of congestion management.

In Section II, some background will be provided regarding the interaction between IoT and cellular network infrastructure as well as related work by other researchers which presents some of the challenges reported in these studies. In Section III, IV and V the model, simulation and results of this investigation are presented, before a conclusion is drawn.

II. BACKGROUND

A. IoT Readiness

The development of a country and economy depends on communication and the way people interact and connect with each other. IoT is a fast emerging shift in networking and communication paradigms for both people and machines. The economic position of a country sadly limits the ability of the country to embrace the possibilities offered by that country. A study was done to assess the readiness of Sub-Saharan African countries to adopt or innovate with IoT to join the rest of the world on the IoT evolution [6].

In Table I, a summary of the study can be seen. Africa houses 35 of the 45 poorest countries in the world, and most of these countries struggle to provide basic needs to people (especially in Sub-Saharan Africa) [9].

Based on the economies of SSA (Sub-Saharan Africa), MENA (The Middle East and North Africa), A/P (Asia and the Pacific), Americas and Europe an IoT index was used to gauge the preparedness of countries to implement IoT. The indices that were used to create the IoT readiness index included; Network Readiness, ICT (information and communication technologies) Development, Global Innovation, Global Competitive, and Knowledge Economic Index (KEI).

TABLE I
IoT READINESS STUDY SUMMARY [9]

Index Type	SSA	MENA	A/P	Americas	Europe
Network Ready	3.80	4.40	4.10	4.40	5.78
Developed Countries	3.80	5.72	7.23	6.40	8.41
Innovative Countries	3.23	—	5.08	4.20	6.0
Competitive Economies	5.77	6.65	7.40	6.55	7.71
Knowledge Driven	3.67	5.87	7.73	6.74	9.02

As can be seen in Table I, Sub-Saharan Africa scored the lowest in all fields, showing that it is the least ready to implement IoT.

In 2013 there were no known documented IoT deployments in Africa as a result of the lack of infrastructure and cost. Fixed broadband subscriptions costs are higher than 30% of the monthly incomes in Africa. However, mobile broadband costs are less than half of fixed broadband costs. Internet connectivity in Africa is much more accessible from mobile phones. Thus rather than continuing to install landline infrastructure why not move straight to mobile [9]. IoT has the potential to solve underlying problems in Africa such as environmental, climate change, agriculture, health and security problems [10], [11].

B. IoT Networks

There are various types of networks that can be used for IoT devices, depending on the implementation and area of application. These networks include LoRa, Sigfox, NB-IoT, LTE-M and GSM Cellular networks [4]. Most of these networks could work seamlessly in Africa, but they still need to be deployed across Africa, which would have financial implications. In the meantime, a viable solution for an IoT network in Africa would be using existing cellular networks which, in turn, holds the advantage of low latency and high data rates [12].

African cellular networks consist mainly of 2G, 3G and 4G technology implementations. Figure 1, summarises the data

gathered and analysed from Ericsson mobile reports, which showed that in 2014, Africa mostly used 2G (80%) and 3G (18%) networks. In 2017, the only difference was the ratio of 2G (50%) and 3G (40%) networks with the implementation of 4G (8%), whereas from this Sub-Saharan Africa only contributes to 5% of the 8% for the region. Finally, a prediction of the mobile usage in 2023 is shown, and even by then the 2G, and 3G Networks still contribute to 53% of African cellular networks. 5G networks would begin rollout in 2020, but Africa will only be using 2% of it in their cellular networks by 2023 [13], [14].

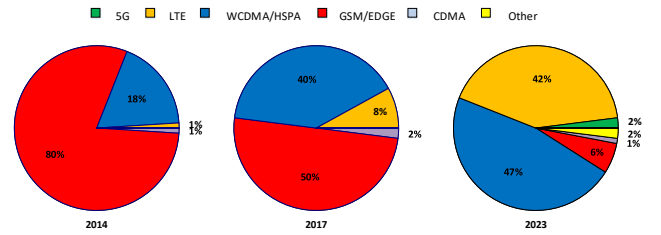


Fig. 1. Mobile Subscriptions in the Middle East and Africa [13], [14]

It is, therefore, a safe assumption that 2G, 3G and 4G cellular networks can be used to create an IoT in Africa. The challenge of using a cellular network in Africa is to determine the capacity of IoT devices that can be used using the current infrastructure and not interfere with daily mobile traffic [15], [6], [12].

C. Cellular Networks

Cellular networks have evolved since the 1980's with the first generation analogue based cellular system. Since then, the second digital based generation with GSM (Global System for Mobile Communication), VAS (Value Added Services), GPRS (General Packet Radio Services) and EDGE (Enhanced Data GSM Environment) was developed. This was followed by an internationally standardised third-generation (3G) mobile system. A fourth-generation (4G) Network was developed using the internet protocol (IP) to have a common platform for all developed technologies [16]. Using 4G technology is less expensive and can transfer data much faster than any previous generation mobile system. Considering how technology has evolved over the past years, the fifth generation (5G) mobile system will be ready and implemented by 2020 [1]. The 5G network is specially designed for the Internet of Things and M2M communication, having low latency standards and faster data transfers than the fourth generation mobile network [15].

D. Applicable standards

There are multiple standardisation organisations to regulate the implementation of network infrastructure, including the ITU, ETSI, ARIB, ANSI and 3GPP. In this study, the ITU standards regarding cellular networks will be used as a point of departure [17].

E. Related Work

With IoT being a current hot topic, there are numerous papers on cellular IoT. Most of these studies focus on LTE cellular networks. The capacity estimation exercise is approached using Mobile Autonomous reporting (MAR) and Network command. The LTE capacity is expressed regarding the number of report per physical resource block (PBR) per hour. Services such as road monitoring and non-residential services report data faster and thus has requirements that use more PBR's per hour [1].

Another approach to capacity estimation on an LTE network was made regarding low data rate applications and high data rate applications for both urban and suburban cases. The capacity estimation (N) was calculated using the allocated time (T), cellular data rate (DR_{cell}) and payload size (P_{APP}) shown in Equation 1. For low data rate applications NB-LTE (Narrow Band LTE) would be best suited, but in the case of high data rate applications such as traffic management, LTE solutions could be taken into account [15].

$$N = \frac{DR_{cell}T}{P_{APP}} \quad (1)$$

In another paper the same PBR method was implemented, this time LTE cellular network was used for IoT deployment, and a capacity estimation was done for both LTE and NB-LTE networks since NB-LTE systems are built from existing LTE functionalities. NB-LTE, however, interferes with the LTE network and can cause coverage problems using co-channel interference and adjacent cell interference. NB-LTE cannot yet be incorporated in current LTE infrastructure [18].

LTE can support large numbers of IoT devices, that would have limited impact on daily cellular traffic. It was found that the average number of devices an LTE cell can handle is 52547 [1].

III. SYSTEM MODEL

Knowing the parameters of an IoT device, the unoccupied space on the cellular network can be allocated to IoT devices. The estimated number of IoT devices is calculated by approaching cellular tower usage with the Erlang, traffic model. This system model is described in Figure 2 and the IoT application used is smart traffic lights [19], [20].

The cellular capacity of each tower is calculated by using the average number of traffic channels (T). The cluster size (K) of the cellular tower can change depending on the environment (path-loss coefficient (α)), carrier to co-channel interference ratio ($\frac{C}{I}$) and the geographic location of the cellular tower. Thus $K=1,3,4,7,9,12,21$ which is demonstrated in Figure 3 and can easily be calculated by the use of Equation 2. The number of traffic channels per cell (N) is calculated using Equation 3 knowing the total channels (T) [19], [20].

$$K = i^2 + ij + j^2 \quad (2)$$

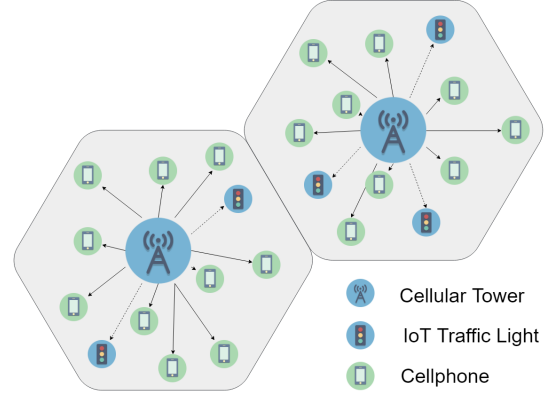


Fig. 2. IoT traffic system model

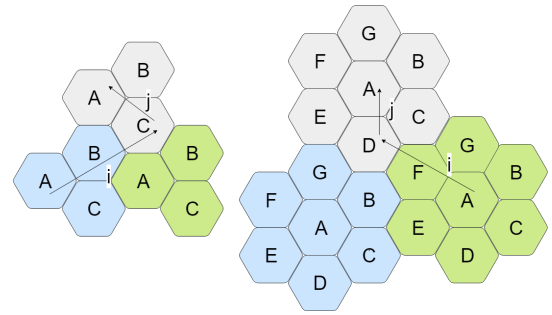


Fig. 3. General representation of a cluster size

$$N = \frac{T}{K} \quad (3)$$

The capacity of the cellular system is calculated with Equation 4 that uses the number of traffic Channels (T) multiplying it with the number of times the cell cluster repeats itself (M), as in Figure 3 $M=3$ in both examples [19], [20].

$$SystemCapacity = M \times T \quad (4)$$

Equation 8 calculates the minimum cluster size (K) required for the geographical location of the cellular tower. Equation 8 is a combination of the co-channel reuse ratio ($\frac{d}{r}$) shown in Equation 5, the propagation model shown in Equation 6 and the carrier to co-channel interference ratio ($\frac{C}{I}$) shown in Equation 7. Thus combining these equations results in the minimum cluster size required for a cellular tower and its parameters [20].

$$\frac{d}{r} = \sqrt{3K} \quad (5)$$

$$P_r = P_t L d^{-\alpha} \quad (6)$$

$$\frac{C}{I} = \frac{P_t L_r^{-\alpha}}{\sum_{j=i}^6 P_t L_d^{-\alpha}} = \frac{1}{6} \left(\frac{r}{d} \right)^{-\alpha} \quad (7)$$

where: P = Propagation, L = constant depending on frequency, d = distance in m, and α = path-loss coefficient

$$K = \frac{1}{3} \left(\frac{6C}{I} \right)^{\frac{2}{\alpha}} \quad (8)$$

The typical $\frac{C}{I}$ value for digital networks are 13-18dB, and α is the path-loss coefficient that is determined by the geographical location of the cellular tower [20].

The IoT capacity estimation uses Erlang traffic approximation. The Erlang value for the maximum traffic a cell tower can handle is read from the Erlang B table, where an average number of traffic channels is used to find the maximum traffic a cellular tower can handle. The IoT device Erlang requirements are calculated with basic IoT device parameters such as the transmission arrival rate (transmissions/hour) and mean holding time (hours/transmission) in Equation 9 [20].

$$E = n\lambda t_h \quad (9)$$

where: λ = transmissions/hour, t_h = hours/transmission

IV. METHODOLOGY

The cellular coverage and map of traffic lights in Potchefstroom, South Africa were used. The capacity of IoT devices, which in this case is traffic lights can only be calculated by knowing the typical parameters. The location of all the traffic lights situated in Potchefstroom was retrieved with Google maps and Google earth and was overlaid on a map in Figure 4. This geographic data was mapped in MATLAB, and the antenna toolbox was used to overlay cellular coverage maps.

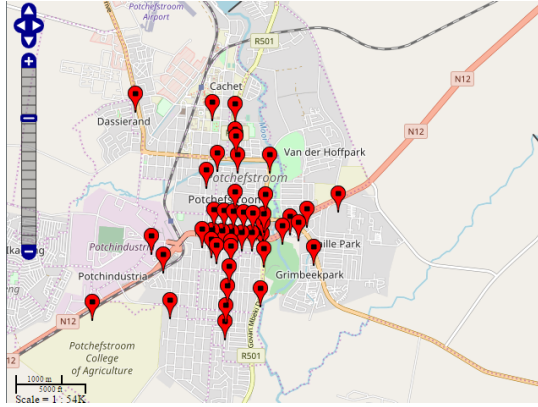


Fig. 4. IoT traffic light locations

The cellular tower information is needed to plot the coverage maps i.t.o 2G, 3G and 4G coverage. These coverage maps are also plotted for the four leading cellular providers in South Africa. The average values across the four carriers were used for the capacity calculations and coverage maps of the cellular towers. These experimental parameters are summarized in Table II [17], [16]. Some acronyms used in the tables: transmitted power (P_{tx}) and Bandwidth (BW).

TABLE II
POTCHEFSTROOM CELLULAR TOWER EXPERIMENTAL PARAMETERS

Parameter	2G	3G	4G
Tx Power	20W	20W	20W
Antenna Height	15-30m	15-30m	15-30m
Signal Strength	Min:-53dBm Max:-89dBm	Min:-55dBm Max:-107dBm	Min:-68dBm Max:-106dBm
BW	200KHz	5MHz	10-15MHz
Data Rate	64kbps	144kbps- 2Mbps	100Mbps- 1Gbps
Frequency Band SA	900MHz/ 1800MHz	900MHz/ 2100MHz	1800MHz/ 2300MHz

According to the literature [21], the average time a traffic light takes to transition between states ranges between 2s and 120s. These experimental IoT device parameters are found in Table III.

TABLE III
IoT DEVICE EXPERIMENTAL PARAMETERS

Parameter	Range
Interval	2s - 120s
Time	100ms
Payload	256KB
Data Rate	64kbps (2G) - 1Gbps (4G)

The calculated cellular capacity is expressed i.t.o Erlang and the IoT device requirements were also approached using the Erlang method, typically found in cellular calling calculations. Erlang is a unit of measure for telecommunication traffic and describes the traffic volume of one hour. An IoT device is seen as a device making short calls over an hour (transmission of data per hour). The cellular capacity Erlang values were used to determine the estimated IoT devices on a Cellular Network.

V. RESULTS

From the results obtained a clear indication of the estimated number of IoT devices that can be connected to an existing cellular network is shown, as well as the coverage maps of the geographical location the model was derived from.

A. Cellular Coverage

Using the obtained data from Cellmapper, as well as the researched data regarding 2G, 3G and 4G cellular networks combined by location pinning in Google Maps, coverage maps were generated. The calculation results and averaged values used for the coverage maps are summarised in Table II and Table IV.

Data from the four leading cellular providers in South Africa was used to map the cellular coverage of Potchefstroom. Figure 5 shows the four cellular providers coverages individually.

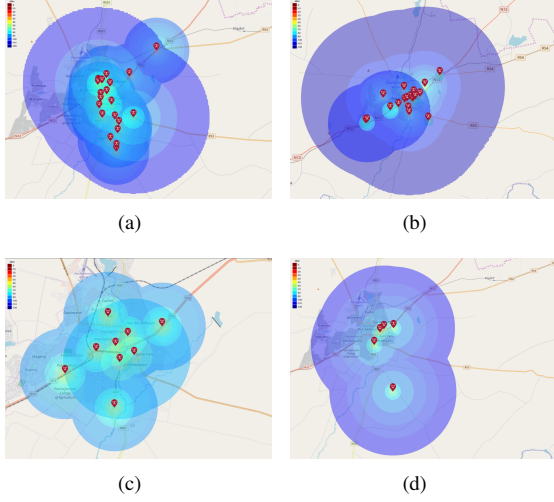


Fig. 5. Potchefstroom Cellular coverage maps of (a) Carrier 1, (b) Carrier 2, (c) Carrier 3 and (d) Carrier 4

Figure 5 compares the coverages of all four cellular providers. Each coverage map is a combination of 2G, 3G and 4G technologies for each cellular provider. Carrier 1 and 2 have more sufficient coverage compared to 3 and 4.

Figure 6 shows the cellular coverage maps of Potchefstroom as well as a coverage map of all the carriers towers combined. The figures were grouped per cellular technology generation, 2G, 3G and 4G as IoT capacity calculations were done for each technology generation.

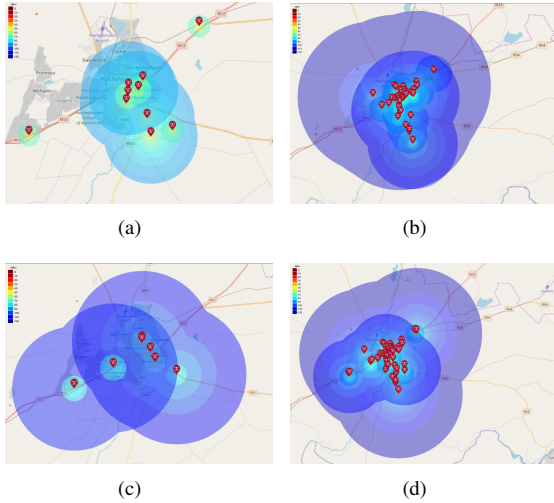


Fig. 6. Potchefstroom Cellular coverage maps of (a) 2G Towers, (b) 3G Towers, (c) 4G Towers and (d) All Towers

In Figure 6, it is clear that the coverage of 2G networks is slowly phasing out and that the 4G network is still emerging in Potchefstroom. The most prominent cellular coverage is thus 3G technology. These results correspond to the research in the background section which concluded that 2G and 3G networks are the most prominent in Africa.

B. Capacity Estimation

Approaching the IoT capacity estimation with the Erlang traffic method, the results from Matlab for 2G, 3G and 4G networks were tabulated in Table IV. The channels used was an average obtained from various cellular calculations. The average blocking probability during busy hours in a cellular system is 1-2%. A worst-case scenario was used in the calculations, and the Erlang capacity value with a 2% blocking probability was read from the Erlang B table.

TABLE IV
2G, 3G, 4G TOWER CAPACITY RESULTS

Parameter	2G	3G	4G
CI	15dB	14dB	13dB
Co-channel reuse ratio (d/r)	3.7114	Cellular	Cellular
Cluster Size(K)	7	7	4
Channels	35	49	56
Channels per Cell(N)	5	7	14
Erlang B table(2%) per cell	1.657E	2.935E	8.200E

The Erlang traffic calculations were done with the specifications provided in Table III, although the maximum transmission interval is 120s, Equation 9 stipulates to use the average transmission value. The average transmission value calculated was 61s and was used as the maximum transmission interval. A summary of the Erlang requirements for traffic light IoT devices is shown in Table V, with an average Erlang value for 1, 20 and 50 devices.

TABLE V
IoT DEVICE ERLANG REQUIREMENTS

1 Device	1 Device	20 Devices	50 Devices
Tx Interval 61s	0.0016E	0.0328E	0.0820E
Tx Interval 2s	0.0500E	1.0000E	2.5000E

Knowing the Erlang capacity of the cellular network, the number of IoT devices had to be calculated. In Table VI, calculation was done with the probability that the cellular network had users for 90%, 95% and 98% where the unused network capacity could be utilised for IoT connectivity. Using Erlang requirements for an IoT device, the calculation was done for the minimum and maximum IoT devices that could be supported on a single 2G, 3G and 4G cellular tower.

TABLE VI
2G,3G,4G POTCHEFSTROOM IOT DEVICE ESTIMATION PER CELL

Available Erlangs	Network Users(%)	IoT Usage(%)	Min IoT Devices	Max IoT Devices
2G				
1.657E	98%	2%	0	20
	95%	5%	1	51
	90%	10%	3	103
3G				
2.935E	98%	2%	1	36
	95%	5%	2	91
	90%	10%	5	183
4G				
8.200E	98%	2%	3	102
	95%	5%	8	256
	90%	10%	16	512

The IoT capacity results in Table VI shows that for a 2G network the minimum and maximum IoT devices are 0 and 103 respectively. In this use case, it is possible for the device minimum to be zero as Potchefstroom has limited 2G coverage. Considering a 3G network in the same location, the minimum and maximum IoT devices are 1 and 183 respectively. Finally, a 4G network can support the most devices in the test location, with an estimated minimum of 3 devices, and a maximum of 512 devices per single cell in a cluster, for the intelligent traffic light scenario considered here.

CONCLUSION

This paper aimed to determine an estimated number of IoT devices that can be connected to an African Mobile Network. By using the Erlang approach, the capacity calculation method was tested on Potchefstroom data as a case study and showed promising results. This method would be deemed sufficient to calculate the estimated capacity and determine if its possible to connect smart IoT traffic lights in African cities using its current cellular infrastructure. Compared to the related work which focuses on LTE and NB-LTE (Narrow Band LTE) networks for IoT, the method for the use case of Potchefstroom showed that 3G networks have more coverage than 4G LTE networks. With the number of 3G towers and IoT capacity estimation, 3G networks provide the best solution for Potchefstroom. The method used can be applied to any African city, and the results would determine which network generation would be sufficient to implement IoT traffic light devices and the estimated number of devices for those cities.

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