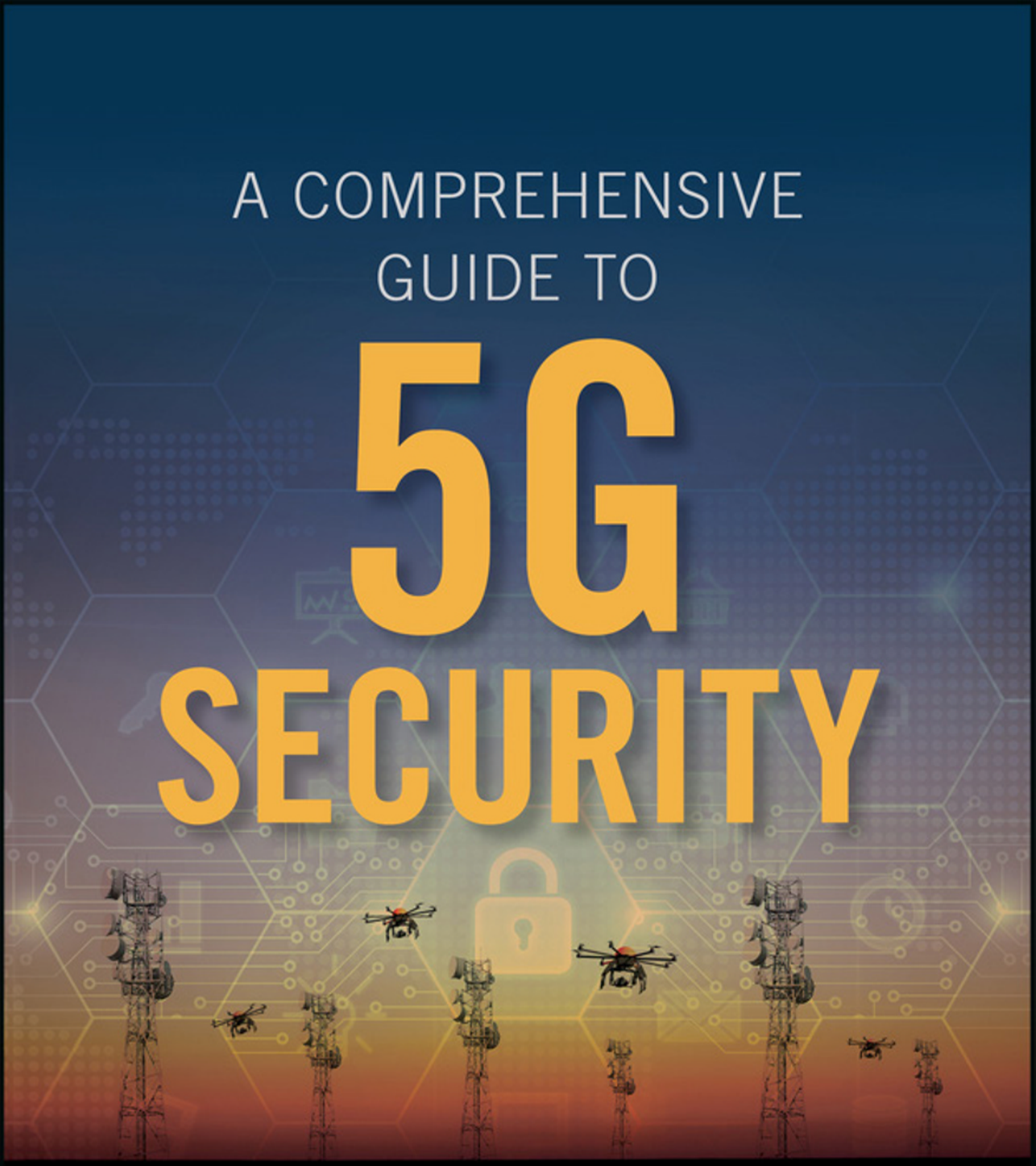
A COMPREHENSIVE GUIDE TO 5G SECURITY



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A Comprehensive Guide to 5G Security

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Foreword

5G cellular networks promise not only an enhancement of radio access technology but also to complete the trajectory to connecting billions of people and things, whether on motion or attached to an infrastructure. By reducing the cost and efforts to connect people and things, it will not only help accelerate economic growth across various industries and the public sector, but will also provide a platform based on cloud computing and IoT (Internet of Things) for many critical infrastructures that offer important utility, transportation and public safety services. It is currently, and will be for the next decade, the prime focus of research and development activities across multiple countries and continents, and the outcome sought will go beyond basic user connectivity services, also addressing opportunities to simplify networks and the deployment of new services.

As 5G networks become pervasive and foundational components of personal, public and enterprise systems, possibly replacing dedicated and isolated networks. Maintaining the confidentiality, integrity and availability of these networks will be among the key design and implementation challenges. Universal connectivity is attractive to both the intended beneficiaries of these networks likewise to the bad actors. They can wreak havoc from afar, across different industries and causing financial, privacy, safety and national security harms.

This book is one of the first attempts to comprehensively address the key security areas and domains for 5G networks, starting from a 5G security landscape overview and physical infrastructure security to an in-depth discussion around security mechanisms for different components of 5G mobile networks. It also provides important insights into the current and future threats to mobile networks and mapping those to the various threat vectors for different mobile generations, including 5G, by using a detailed threat analysis approach. Readers will find an opportunity to explore the evolved security model and lifecycle functions for 5G. This book has taken a fresh perspective on addressing security and privacy for new areas evolving with 5G, including Device to Device (D2D) connectivity, cloud services, SDMN (Software Defined Mobile Networks), NFV (Network Function Virtualization) and IoT (Internet of Things).

The book will be helpful to a range of 5G stakeholders: researchers looking for challenging new problems, mobile network operators (MNOs) and virtual network operators (MVNOs), seeking to plan for the new threat environment, owners of infrastructure investigating how 5G can improve their operations, telecom equipment vendors, and standardization bodies working on network and IoT standards.

Henning Schulzrinne
Chief Technology Officer
Federal Communications Commission,
The United States of America

Preface

The emergence of smartphones and tablets coupled with broadband wireless connectivity has changed our lives. More demands on high throughput, low latency, high-speed mobility and new services drive the development of 5G. The first commercial networks of 5G are expected for deployment by 2020, three years ahead of writing this book. However, initial proof-of-concept deployments are announced already for 2018. While multiple books already exist on 5G, this is the first book, to our knowledge that focuses on security aspects of future 5G ecosystem.

The book provides a reference material to a comprehensive study of 5G security. It offers an insight into the current and future threats to mobile networks and mechanisms to protect it. It covers the critical lifecycle functions and stages of 5G security, and how to build an effective security architecture for 5G based mobile networks. It addresses mobile network security based on Network-centricity, Device-centricity, Information-centricity and most importantly, People-Centricity views.

This book offers security considerations for all relative stakeholders of mobile networks, such as mobile network operators (MNOs), mobile virtual network operators (MVNOs), mobile users, wireless users, Internet-of-Things (IoT) and cybersecurity experts, security researchers and engineers.

5G Mobile Networks

5G networks are not only expected to be faster, but provide a backbone for many new services for Networked Society, such as IoT and the Industrial Internet. Those services will provide connectivity for autonomous cars and Unmanned Aerial Vehicles (UAVs), remote health monitoring through body-attached sensors, smart logistics through item tracking, remote diagnostics and preventive maintenance of equipment. Most services will be integrated with cloud computing and novel concepts such as mobile edge computing, which requires smooth and transparent communications between user devices, data centers and operator's networks. New classes of Quality-of-Service (QoS), such as low-latency ultra-reliable communication as well as energy-efficient sensor connectivity, will hopefully be supported by 5G.

New radio bands above 20 GHz are being allocated for 5G. Since the current LTE systems already approach the theoretical limits of spectrum efficiency use, higher rates in the 5G can only be achieved by using millimeter-wavelength bands with challenging propagation properties in combination with very small cells. This is also needed to

achieve extremely high density of users per geographical area. Providing radio communication at high speeds and low power, as well as seamless roaming and network mobility, remain major challenges for 5G. Physical layer security on the radio level may prove to be an important challenge for 5G technology.

5G is presently under development by telecommunication vendors, EU projects (5G-ENSURE) and frameworks, and the 5G Infrastructure Public Private Partnership (5G PPP). Many of the vendors have provided their vision of 5G services and security models in White Papers. However, the standardization process of 5G is just starting within 3GPP, although other standardization bodies, such as the Internet Engineering Task Force (IETF), are continuously developing new secure protocols and architectures to be utilized in 5G. It is important that 5G networks are securely designed and standardized from the beginning, rather than adding security as an afterthought.

Although security models of 3G and 4G networks based on Universal SIM cards worked well, 5G security cannot be a carbon copy of existing designs, due to new requirements. Initially, the main motivation for security in cellular networks was the right functioning of the billing system, followed by encryption of the radio interface. Location and identity privacy of the user were also supported, followed by two-way authentication in 3G to prevent fake base stations. 4G added state-of-the-art cryptographic protocols and protection of physical tampering with the base stations, which could be installed on user premises. While all those security properties are still valid, 5G will face additional challenges due to increased user privacy concerns, new trust and service models and requirements to support IoT and mission-critical applications.

The Need for Security

Phone hacking was first spotted somewhere between the 1960s and 1970s, when phreakers demonstrated their skills to manipulate the functions of a telephone network. Methods to attack telecommunication systems have evolved since then and have changed shape from war dialers to viruses to worms to modern-day advance persistent threats. Tools to protect our telecommunication systems have also evolved from physical access control to antivirus to modern application and context aware firewalls.

Increased use of smartphones for data services and applications has exposed these devices to the same security threats that were once known and dedicated to personal computers (PCs). Mobile devices have replaced legacy system and have changed our ways to learn, work, entertain, shop and travel. Bring Your Own Device (BYOD) and cloud technologies have further diminished the enterprise boundaries and often challenged security experts to work out of the box strategies.

Motivations for attacking networks have also changed from fun-loving immature script kiddies to organized cybercrime rings and hacktivists with clear political and financial objectives. In this age of digitalization, whereafter connecting humans using Internet and mobile, we are talking about connecting things and machines. The mobile has not yet completely replaced the personal computer but has become an ideal place where personal information can be found for nefarious use. Therefore, security needs to be architected to not only protect from the current threats but to address the increasing and evolving threat landscape. Adequate security should include threat intelligence, visibility and real time protection.

On the other hand, today's networks host various values – examples include revenue streams and brand reputation. The accessibility of these values via the Internet has already attracted hacktivists, underground economies, cybercrime and cyber-terrorists. The values hosted in, and generated by, the 5G system are estimated to be even higher, and the assets (hardware, software, information and revenue streams) will be even more attractive for different types of attacks. Furthermore, considering the possible consequences of an attack, the damage may not be limited to a business or reputation; it could even have a severe impact on public safety.

This leads to a need to strengthen certain security functional areas. Attack resistance needs to be a design consideration when defining new 5G protocols. Security and privacy are cornerstones for 5G to become a platform for the Networked Society. Cellular systems pioneered the creation of security solutions for public communication, providing a vast, trustworthy ecosystem – 5G will drive new requirements due to new business and trust models, new service delivery models, an evolved threat landscape and an increased concern for privacy.

5G is going to offer similar impact to communication as once "fiber" technology did; it has the potential to transform the mobility concept. Applications for 5G are beyond the traditional mobile connectivity needs to new public communication, IoT, smart world based out of smart cities, smart transportation and more. One of the major challenges for 5G adoption is security related challenges.

To the best of our knowledge, no book is published yet that addresses the 5G security, comprehensively, and very little is written on this topic. Although the security is the mandatory requirement of 5G networks, many of the 5G security related issues are still under development. However, the rapid adaptation of 5G network will soon raise the requirement of a comprehensive handbook of 5G security.

5G Security Standardization

At the time of writing, 5G standardization has not yet started as the system architecture is still in research phase. Despite its name, the Third Generation Partnership Project (3GPP) continues its work for defining also 5G specifications. In February 2017, 3GPP published "Service Requirements for the 5G system" (TS22.261) that defines performance targets in various scenarios such as indoor, urban, rural and different applications (intelligent transport, remote monitoring, etc.). 3GPP plans to publish 5G Phase 1 specifications in 2018 as Release 15 and Phase 2 in 2020 as Release 16.

Since 5G is expected to be completely converged with Internet protocols, the standards produced by the Internet Engineering Task Force (IETF) in Request for Comments (RFCs) are expected to play a key role. The relevant Working Groups are, for example, IP Wireless Access in Vehicular Environments (IPWAVE) WG and Host Identity Protocol (HIP) WG on secure mobility protocols.

If 5G networks will serve safety-crucial applications as envisaged, the ISO (International Organization for Standardization) will introduce standards such as Common Criteria (ISO 15408) will apply. For instance, for car connectivity, a specific standard is ISO 26262, which covers car safety requirements. For tele-health, EU and USA-specific standards, such as HIPAA (Health Insurance Portability and Accountability

Act) and internationally ISO 27799. For smart cities and smart grids, standards of IEC (International Electrotechnical Commission) and compliance to, for example, North American Electric Reliability Corporation (NERC) will be needed.

ETSI (European Telecommunications Standards Institute) was the creator of GSM standard and key contributor of W-CDMA as 3G standard within 3GPP. As a co-founder of 3GPP, ETSI is actively involved in developing 5G through organizing such events as "ETSI Summit on 5G Network Infrastructure", which focused on 5G standardization in 2017. ETSI identified priority applications for 5G as mobile broadband evolution, massive M2M communication, and ultra-reliable low latency communication. ETSI is also a known contributor to the Network Functions Virtualization Industry Specification Group (ISG) and is currently reforming a group focusing on 5G security.

ITU (International Telecommunication Union) receives input from regional organizations such as ETSI in Europe and ARIB in Japan and develops recommendations for standards-defining bodies. ITU Telecommunication Standardization Sector (ITU-T) created a Focus Group on International Mobile Telecommunications (IMT-2020), which operated in 2015-2016 and analyzed requirements and framework for the 5G ecosystem. ITU Study Group 17 (SG 17) focuses entirely on security aspects of telecommunication.

Several other relevant Standardization Bodies include IEEE 802, TCG and ONF. Interoperability and mobility with third-party networks such as WiFi involves standards from the IEEE (Institute of Electrical and Electronics Engineers) such as 802.11. At Trusted Computing Group (TCG), the Mobile Platform Work Group (MPWG) develops uses cases, frameworks and analyses of 5G security. Open Networking Foundation (ONF) promotes the use of software-defined networking protocols and network operating systems. Its specifications, including OpenFlow, could become a part of 5G core architecture and therefore are also important from the security viewpoint.

Intended Audience

This book will be of key interest for multiple groups of researchers, engineers and business persons working on 5G development and deployment:

- *Mobile Network Operators (MNOs)*: as they will be looking to adopt 5G technology to offer new and state-of-the-art secure services to their customers. This book will offer the required guidelines, methods, tools and mechanisms to secure their network while embracing for 5G.
- *Mobile Virtual Network Operators (MVNOs)*: would like to equally reach the large customer base that is going to switch to 5G networks. Security is the key requirement while connecting MVNOs with the core networks of large operators.
- *Telecommunication researchers*: 5G security is one of the key areas of interest for telecommunications researchers, as security challenges outpace the traditional tools available on the market. This book will offer a single source of all the security related topics for 5G researchers and provide leads for basics of 5G security.
- *Academics*: Mobile network security has already been an area of research and study for major educational institutions across the world. With 5G evolvement as the future of mobile networks, there is no such other reference book available that academics can use for teaching this critical area of interest.

- *Technology Architects and Standardization Bodies*: 5G is going to cross the traditional mobility borders and is going to have an equal impact on enterprises and organizations who are planning to transform into digital businesses. It would be critical for architects to start aligning their technology and security architectures to the future needs of 5G standards. This book offers resources to design and build a security architecture and maintain it.
- *IoT and Industrial Internet experts*: Internet of things is going to change the way industrial networks are built, and 5G is going to provide the underlying platform for IoT networks. Security has remained the top priority for industries due to criticality and sensitivity of the data and information flows in their networks. Advance knowledge of 5G security principles, components and domains is going to help industries lay a foundation of IoT security. This book will provide the guidelines and best practices for 5G-based IoT security.

Book Organization

The book is divided into four parts covering various aspects of 5G security ecosystem: Security Overview, Network Security, Device and User Security, and Cloud and Virtual Network Security.

The first part provides an introduction to 5G and history of preceding systems, an overview of 5G security architecture, and general aspects of telecommunication security. The first chapter describes the evolution of cellular systems. For each generation, from 1G to current 4G, its architecture and security mechanisms are presented. The second chapter focuses on 5G mobile networks from the viewpoint of requirements and enabling technologies. The main 5G system components (radio, core, end-to-end), standardization and research activities are surveyed. The third chapter on mobile network security landscape describes attacks possible in the existing and previous generation mobile communication systems. Severity and estimated frequency of threats are analyzed, concluded by the evolved 5G security model. The fourth chapter considers secure 5G software-defined network architecture. The fifth chapter concludes Part I with an overview of cyber-security preparedness framework.

Part II takes an in-depth look at security of core and radio interfaces. Chapter 6 introduces radio signal watermarking as a way to achieve security at the physical layer. The application of this concept to 5G architecture is proposed. Chapter 7 treats interoperability between 5G and Wireless LANs (WLANs) from the security viewpoint. This chapter compares possible attacks in 5G and WLANs and proposes a common interoperability architecture. Chapter 8 focuses on safety of physical infrastructure in 5G. Structural resilience of mast poles to natural disasters and deliberate attacks by humans are described. Chapter 9 is dedicated to Customer Edge Switching (CES). It is a security framework for 5G, which extends functionality of Network Address Translation (NAT) at the edges. Finally, Chapter 10 introduces a Software Defined Security Monitoring for 5G Networks. The use of novel Software Defined Networking (SDN) and Network Function Virtualization (NFV) concepts in 5G monitoring systems can address the classical weaknesses in legacy monitoring systems.

Part III considers security outside of the operator's part of the 5G network; namely, on user equipment such as smartphones and embedded modems and the users themselves.

The main topics concern security of the Internet of Things (IoT), privacy and authentication of users, and positioning security. Chapter 11 describes security of Internet of Things (IoT) when connected over 5G. A special consideration is given to wireless connectivity of robots, such as Unmanned Aerial Vehicles (UAVs). Chapter 12 handles user privacy in 5G, including location, identity and data privacy. Trust models and Identity management are considered. Chapter 13 performs a deeper investigation of secure device positioning in 5G. Outdoor and indoor positioning mechanisms are compared in the content of 5G, and their security threats and avoidance methods are analyzed.

Part IV is dedicated to cloud technologies and network virtualization security. Chapter 14 describes the roles and security models of Mobile Virtual Network Operators (MVNO) in 5G. Possible attacks on hypervisors, virtual machines and software-defined components to compromise availability, integrity and Authentication, Authorization, Accounting (AAA) are considered. Chapter 15 handles security of Network Function Virtualization (NFV) and related services in 5G networks. NFV driving forces, secure lifecycle and multi-tenancy issues, policy and machine learning in NFV are discussed. Chapter 16 introduces a concept of Mobile Edge Computing (MEC) in 5G. Various security challenges for MEC, possible attacks and secure architectures are described. The final chapter, Chapter 17 takes a look the regulatory aspects of privacy and security in 5G. The legal framework, relevance analysis, and technology implications can be found there.

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Part I

5G Security Overview

1

Evolution of Cellular Systems

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1.1 Introduction

Wireless communication technologies are essential parts of our lives. From WiFi home networks to sophisticated machine-to-machine communication in the robotics industry, we live in a world of wireless connectivity and it is impossible to imagine a single day without using any wireless devices. The blessings of cellular technologies provided us with a great deal of mobility and thus made it possible to listen to the radio while travelling in a car or on the beach. The cellular devices are also convenient in that we no longer have to worry about the size of the cables to connect to the networks. We are now living in a world where conferences for business meetings, distance and online courses from universities, and medical help over long distances are considered as part and parcel of our daily lives. We have greater access to information than ever before and it is all possible due to the advancements and inventions in cellular communication.

The number of cellular users increased dramatically over the last decade compared to the other technologies and are still increasing. We can see from Figure 1.1 that the fixed broadband or fixed wired subscription did not increase that much in a last decade, while the mobile cellular subscriptions are increasing day by day. With the advent of sophisticated technologies, such as tactile computing, autonomous vehicles, wireless charging, smart living, etc., we can only envision how the use of cellular technologies will grow in the future.

This chapter is dedicated towards the evolution of cellular communication. In that respect, we start by discussing the initial developments and history of cellular systems. We subsequently go through the different generations of cellular systems and have a brief discussion about them. As the topic is broad, we try to confine ourselves to the basic information related to the radio interfaces and network architecture of different generations. We align the chapter with the focus of the book by discussing the evolution of security measurements during each generation.

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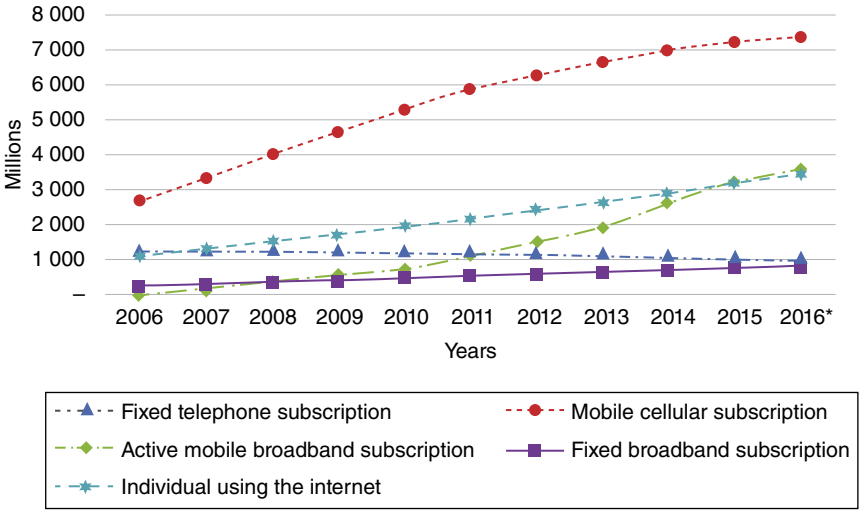

Figure 1.1 Growth of communication services encompassing the last decade.

1.2 Early Development

Wireless communication in its current practice is a very sophisticated technology, making long distance voice, data and multimedia communication possible between people, no matter which part of the world they reside in. The kind of evolution that wireless cellular technologies went through, in particular over the last three decades, and over the last two hundred years in general, makes for a fascinating journey. If we try to trace the initial efforts that became the foundation of the wireless communications of today, we have to go back as early as the ancient Greek, Roma and Chinese cultures, where electrical and magnetic properties of materials were experimented on. The early experiments on electrical and magnetic properties were not intended for wireless communication, since that sort of vision was not present as a motivation for these experiments.

We see that even in the 19th century, when the connection between electricity and magnetism was first developed, the intuition and imagination of what it could achieve was naturally missing amongst the researchers. It is good to say that it was mostly the random experiments that eventually led to the kind of communication systems we have now, and that is something which makes this journey more interesting. Even though, as mentioned above, the experiments towards trying to find electrical and magnetic properties in various ancient cultures, and considered as one of the foremost steps in this journey, it is also important to keep in mind that the last two hundred years present a more coherent and consistent picture that is paved with ground-breaking discoveries.

So, in our analysis the last two hundred years are of primary importance. We have to try to coherently present the connection of all those discoveries as to how one discovery led to another, and what became the motivation to carry out further discoveries. Until this decade, the story is not as linear and direct as it might appear when looking back to its destination. But as far as wireless communications are concerned, it would be unfair

and unimaginative to consider this point in time as the final destination, because as far as wireless communication is concerned, the sky is the limit, or even beyond [9].

Starting with the last two hundred years, say the year 1820, the Danish physicist Hans Christian Ørsted, during one of his lectures noticed that when the current from a battery was switched on and off, a compass needle showed the deflection. This observation led him to discover that an electric field creates a magnetic field; more particularly, an electric current produces a circular magnetic field as it flows through a wire.

The connection between electricity and magnetism was of immense importance that rapidly led to further developments. However, it is sometimes claimed that it was Gian Domenico Romagnosi who discovered this connection around two decades before, but the importance of this discovery cannot be considered insignificant. From the years 1823 to 1826, Dominique François Jean Arago, a French mathematician and physicist, discovered something called rotary magnetism, which was termed Arago's rotation. In simple words, he showed that a wire can become a magnet when current flows through it, and that most bodies could be magnetized. These discoveries were further explained by Michael Faraday later. André-Marie Ampère, another French physicist and mathematician, discovered electrodynamics. Ampère showed that two parallel wires carrying electric currents attract or repel each other, depending on whether the currents flow in the same or opposite directions. Ampere's initial plan was to gain more understanding between electricity and magnetism, and this had led him to these discoveries.

Michael Faraday's contributions are very significant in this journey, and he deserves all the credit that we can give him. After Ørsted had discovered the phenomenon of electromagnetism, it motivated many scientists to study this further, the efforts which helped Ampere in his discoveries. Similar motivation led Michael Faraday to carry out experiments, whereby he successfully managed to build two devices to produce electromagnetic rotation. Not only did he discover electromagnetic induction, but also predicted that electromagnetic forces extended the empty space around the conductor. In simple words, he predicted the existence of electromagnetic waves, which proved to be a true prediction later.

Samuel Finley Breese Morse, an American painter, invented the single-wired telegraph system. He was also a co-developer of the Morse code. This discovery also became possible because of the discovery of electromagnetism. The telegraph was important because it was a first attempt to use electromagnetism in an effort to communicate. The list of discoveries continued in the rest of the 19th century, and the German physiologist and physicist Hermann Ludwig Ferdinand von Helmholtz, worked on the phenomenon of electrical oscillation in 1847, which in itself was not a major contribution, but led to the major contribution by Heinrich Rudolf Hertz, one of his students, who later demonstrated electromagnetic radiations. In 1853, William Thomson also contributed in the form of calculating the period, damping and intensity, as the function of the capacity, self-inductance and resistance of an oscillatory circuit. Another proof of Helmholtz's work came from a discovery by Feddersen, who verified the resonant frequency of the tuned circuit, which was suggested by Helmholtz earlier.

James Maxwell is a prominent and influential name in the progression of wireless communication. He proved the existence of electromagnetic waves by formulating the electromagnetic theory of light and developed the general equations of the electromagnetic field, known as Maxwell equations. The most significant aspect of his work was that for the first time it was demonstrated that electricity, magnetism and also light are

manifestations of the same phenomenon. This discovery is of absolute importance, because it led to the prediction that radio waves exist, which was a very significant finding for the development of wireless communication. In 1866, the first transatlantic telegraph cable was installed and operated by using the Morse code, with a speed of five words per minute.

The first description of transmission of a wireless signal came in the form of a patent by the American dentist Dr Mahlon Loomis, in 1866. It was the idea of the wireless telegraph, from which he supposedly demonstrated the transmission of a wireless signal between two mountains. In 1882, another patent appeared in terms of wireless signal transmission, when American physicist Amos Emerson Dolbeam, transmitted a wireless signal using an induction coil, microphone, telephone receiver and a battery. In 1887, Hertz, a student of Helmholtz, sent and received wireless waves, using a spark transmitter and a resonator receiver. In 1895, Morse coded wireless signals were transmitted for more than over a mile by Guglielmo Marconi, and he carried out successful reception of a Morse coded wireless signal in 1901, which was sent across the Atlantic. In 1904, the patent of the diode came from J.A. Fleming. The triode amplifier was patented in 1906 by Lee DeForest. In the same year, Fessenden transmitted the first speech signal wirelessly. In 1907, the commercial Trans-Atlantic wireless service was started, which used huge ground stations. In 1915, wireless transmission of voice signals was carried out between New York and San Francisco.

Marconi carried out other ground-breaking and pioneering work in wireless communications by transmitting radio signals over long distances in 1920. Prior to that, Marconi was already working on the concept of wireless telegraphy. The breakthrough in his work came with his conclusion that if the height of the antenna could be raised, then the range of radio signal transmission could be extended, which he developed based on wireless telegraphy, where he grounded his transmitter and receiver. With these improvements, he managed to transmit a signal over 2 miles. He discovered short-wave radio, with wavelengths between the 10 and 100 meters range.

In 1920, we had our first commercial radio broadcast. In 1921, the police car dispatch radios came on the scene. In 1930, the television broadcast experiments were started by the BBC. In 1935, the first telephone call was made around the world. World War II led to rapid advancements in radio technology. In 1947, W. Tyrell proposed hybrid circuits for microwaves, and H.E. Kallaman constructed the VSWR indictor meter. In 1955, John R. Pierce proposed using satellites for communications. Sony marketed the first transistor radio. In 1957, the Soviet Union launched Sputnik I, which transmitted telemetry signals for about five months. The carterfone was a device invented in 1968 by Thomas Carter, which connected a two-way radio to the telephone system, letting one person on the radio talk to another person on the phone.

1.3 First Generation Cellular Systems

The prime developers of the first generation (1G) cellular network were the United States, Japan and some parts of Europe. It was based on analog modulation to provide voice services. In 1979, commercial cellular systems were implemented by Nippon Telephone and Telegraph Company (NTT) in Japan. Nordic Mobile Telephone (NMT-400) is a system developed in 1981 that supports international roaming and automatic handover.