1 History

For better or worse, wireless communications have become integrated into many aspects of our daily lives. When communication systems work well, they almost magically enable us to access information from distant, even remote, sources. If one were to take a modern "smart" phone a couple of hundred years into the past, one would notice a couple of things very quickly. First, most of the capability of the phone would be lost because a significant portion of the phone's capabilities are based upon access to a communications network. Second, being burned at the stake as a witch can make for a very bad day.

There are many texts that present the history of wireless communications in great detail, for example in References [186, 48, 146, 304, 61]. Many of the papers of historical interest are reprinted in Reference [348]. Because of the rich history of wireless communications, a comprehensive discussion would require multiple texts on each area. Here we will present an abridged introduction to the history of wireless communications, focusing on those topics more closely aligned with the technical topics addressed later in the text, and we will admittedly miss numerous important contributors and events.

The early history of wireless communications covers development in basic physics, device physics and component engineering, information theory, and system development. Each of these aspects is important, and modern communication systems depend upon all of them. Modern research continues to develop and refine components and information theory. Economics and politics are an important part of the history of communications, but they are largely ignored here.

1.1 Development of electromagnetics

While he was probably not the first to make the observation that there is a relationship between magnetism and electric current, the Danish physicist Hans Christian Ørsted observed this relationship in 1820 [239] and ignited investigation across Europe. Most famously, he demonstrated that current flowing in a wire would cause a compass to change directions. Partly motivated by Ørsted's results, the English physicist and chemist Michael Faraday made significant advancements in the experimental understanding of electromagnetics [304] in the early 1800s. Importantly for our purposes, he showed that changing current in

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one coil could induce current in another remote coil. While this inductive coupling is not the same as the electromagnetic waves used in most modern wireless communications, it is the first step down that path. The Scottish physicist James Clerk Maxwell made amazing and rich contributions to a number of areas of physics. Because of his contributions in the area of electromagnetics [211], the fundamental description of electromagnetics bears his name. While Maxwell might not immediately recognize them in this form, Maxwell's equations in international system of units ("SI") [290, 178] are the fundamental representation of electromagnetics and are given by

$$\begin{aligned} \nabla \cdot \mathbf{d} &= \rho \\ \nabla \cdot \mathbf{b} &= 0 \\ \nabla \times \mathbf{e} &= -\frac{\partial \mathbf{b}}{\partial t} \\ \nabla \times \mathbf{h} &= \mathbf{j} + \frac{\partial \mathbf{d}}{\partial t}\,, \end{aligned} \tag{1.1}$$

where ∇ indicates a vector of spatial derivatives, $\cdot$ is the inner product, $\times$ is the cross product, t is time, ρ is the charge density, $\mathbf{j}$ is the current density vector, $\mathbf{d}$ is the electric displacement vector, $\mathbf{e}$ is the electric field vector, $\mathbf{b}$ is the magnetic flux density vector, and $\mathbf{h}$ is the magnetic field vector. The electric displacement and electric field are related by

$$\begin{aligned} \mathbf{e} &= \epsilon\, \mathbf{d} \\ \mathbf{b} &= \mu\, \mathbf{h}\,, \end{aligned} \tag{1.2}$$

where ϵ is the permittivity and μ is the permeability of the medium. These are the underpinnings of all electromagnetic waves and thus modern communications. In 1888, the German physicist Heinrich Rudolf Hertz convincingly demonstrated the existence of the electromagnetic waves predicted by Maxwell [144, 178]. To demonstrate the electromagnetic waves, he employed a spark-gap transmitter. At the receiver, the electromagnetic waves coupled into a loop with a very small gap across which a spark would appear. The spark-gap transmitter with various modifications was a standard tool for wireless communications research and systems for a number of following decades.

1.2 Early wireless communications

In the late 1800s, significant and rapid advances were made. Given the proliferation of wireless technologies and the penetration of these technologies into every area of our lives, it is remarkable that before the late 1800s little was known about even the physics of electromagnetics. Over the years, there have been various debates over the primacy of the invention of wireless communications. Who invented wireless communications often comes down to a question of semantics. How many of the components do you need before you call it a radio? As is often true in science and engineering, it is clear that a large number of individuals performed research in the area of wireless communications or, as it was often called, wireless telegraphy. The following is an incomplete list of important contributors.

In 1872, before Hertz's demonstration, a patent was issued to the American[1] inventor and dentist Mahlon Loomis for wireless telegraphy [193]. While his system reportedly worked with some apparent reliability issues, his contributions were not widely accepted during his life. This lack of acceptance was likely partly due to his inability to place his results in the scientific context of the time.

In 1886, American physicist Amos Emerson Dolbear, received a patent for a wireless communication system [82]. This patent later became a barrier to the enforcement of Guglielmo Marconi's patents on wireless communications in the United States, until the Marconi Company purchased Dolbear's patent. It is worth noting this demonstration was also before Hertz's demonstration.

In 1890, the French physicist Edouard Eugene Desire Branly developed an important device used to detect electromagnetic waves. The so-called "coherer" employed a tube containing metal filings filling a gap between two electrodes and exploited a peculiar phenomenon of these filings [279]. When exposed to radio-frequency signals, the filings would fuse or cling together, thus reducing the resistance across the electrodes. British physicist Sir Oliver Joseph Lodge refined the coherer by adding a "trembler" or "decoherer" that mechanically disrupted the fused connections. Many of the early experiments in wireless communications employed variants of the coherer.

The Serbian-born, American engineer Nicola Tesla was one of those larger-than-life characters. He made significant contributions to a number of areas of engineering, but with regard to our interests, he received a patent for wireless transmission of power in 1890 [309] and demonstrated electromagnetic transfer of energy in 1893 [310]. Tesla is rightfully considered one of the significant contributors to the invention of wireless communications.

Bengal-born Indian scientist Jagdish Chandra Bose contributed significantly to a number of areas of science and engineering. He was one of the early researchers in wireless communication and developed an improved coherer. In 1885, he demonstrated radio communication with a rather dramatic flair [107]. By using a wireless communication link, he remotely set off a small explosive that rang a bell. His improved coherer was a significant contribution to wireless communications. His version of the coherer replaced the metal filings with a metal electrode in contact with a thin layer of oil that was floating on a small pool of mercury. When exposed to radio-frequency signals, the conductivity across the oil film would change. Marconi used a similar coherer for his radio system.

The German physicist Karl Ferdinand Braun developed a number of important technologies that contributed to the usefulness of wireless communication. He developed tuned circuits for radio systems, the cat's whisker detector (really an

[1] Throughout this chapter we employ the common, if imprecise, usage of "American" to indicate citizen of the United States of America.

early diode), and directional antenna arrays. In 1909, he shared the Nobel Prize in physics with Guglielmo Marconi for his contributions.

The Russian physicist Alexander Stepanovich Popov presented results on his version of a coherer to the Russian Physical and Chemical Society on May 7th, 1895 [304]. He demonstrated links that transmitted radio waves between buildings. As an indication of the importance of this technology to society, in the Russian Federation, May 7th is celebrated as Radio Day.

The Italian engineer Guglielmo Marconi, began research in wireless communications in 1895 [304] and pursued a sustained, intense, and eventually well-funded research and development program for many years to follow. He received the Nobel Prize in physics (with Karl Ferdinand Braun) in 1909 for his contributions to the development of wireless radios [304]. While he is not the inventor of radio, as is sometimes suggested, his position as principal developer cannot be dismissed. His research, development, and resulting company provided the impetus to the commercialization of wireless communications. In 1896 Marconi moved to England, and during that and the following year he provided a number of demonstrations of the technology. In 1901, he demonstrated a transatlantic wireless link, and in 1907 he established a regular transatlantic radio service.

A somewhat amusing (or annoying if you were Marconi) public demonstration of the effects of potential interference in wireless communications was provided in 1903 by British magician and inventor Nevil Maskelyne [146]. Maskelyne was annoyed with Marconi's broad patents and his claims of security in his wireless system. During a public demonstration of Marconi's system for the Royal Institution, Maskelyne repeatedly transmitted the Morse code signal "rats" and other insulting comments which were received at the demonstration of the system, which was supposedly immune to such interference. Previously, in 1902, Maskelyne had developed a signal interception system that was used to receive signals from Marconi's ship-to-shore wireless system. Marconi had claimed his system was immune to such interception because of the precise frequency tuning required for reception.

In the first few decades of the twentieth century, wireless communication quickly evolved from a technical curiosity to useful technology. An important technology that enabled widespread use of wireless communication was amplification. The triode vacuum-tube amplifier was developed by American engineer Lee de Forest. He filed a patent for the triode (originally called the de Forest valve) in 1907 [95]. The triode enabled increased power at transmitters and increased sensitivity at receivers. It was the fundamental technology until the development of the transistor decades later.

In the late 1910s, a number of experimental radio broadcast stations were constructed [304]. In the early 1920s, the number of radio broadcast stations exploded, and wireless communications began its integration into everyday life.

During the Second World War, the concept of tactical communications underwent dramatic development. The radios became small enough and sufficiently robust that a single soldier could carry them. It became common for various military organizations to make wireless communications available to relatively small groups of soldiers, allowing the soldiers to operate with greater effectiveness and with access to external support. By the end of the Second World War, American soldiers had access to handheld "handie-talkies," [265], such as the Motorola SCR-536 or BC-611, that are recognizable as the technical forebearers of modern handheld communications devices.

1.3 Developing communication theory

In 1900, Canadian-born American engineer Reginald Aubrey Fessenden [304], employed a high-frequency spark-gap transmitter to transmit an audio signal by using amplitude modulation (AM). Fessenden also developed the concept of the heterodyne receiver at about the same time, although the device technology available at that time did not support its use. The heterodyne receiver would multiply the signal at the carrier frequency by a tone from a local oscillator, so that the beat frequency was within the audible frequency range.

In 1918, American engineer Edwin Howard Armstrong extended the heterodyne concept, denoted the superheterodyne receiver, by having the mixed signal beat to a fixed intermediate frequency. A second stage then demodulates the intermediate frequency signal down to the audible frequency range. This approach and similar variants has become the standard for most of modern communications. In 1933, Armstrong also patented another important communications concept, frequency modulation (FM).

If one had to pick the greatest single contribution to communications, most researchers would probably identify the formation of information theory [284], published in 1948 by American mathematician and engineer Claude Elwood Shannon. In his work, Shannon developed the limits on the capacity of a communication channel in the presence of noise. It is worth noting the contributions of American engineer Ralph Vinton Lyon Hartley, who developed bounds for the number of levels per sample with which a communication system can communicate at a given voltage resolution [138]. Hartley's results were a precursor to Shannon's results.

The observation by Shannon that, even in non-zero noise, effectively error-free communication was possible theoretically, increased the motivation for the development of error-correction codes. Examples of early block codes to compensate for noise were developed by Swiss-born American mathematician and physicist Marcel J. E. Golay [113] and American mathematician Richard Wesley Hamming [134]. Over time, a large number of error-correcting codes and decoding algorithms were developed. The best of these codes closely approached the Shannon limit.

Developed during the Second World War and published in the 1949, American mathematician, zoologist, and philosopher Norbert Wiener presented statistical signal processing [346]. In his text, he developed the statistical signal processing techniques that dominate signal processing to this day. Addressing a similar set of technical issues, prolific Russian mathematician Andrey Nikolaevich Kolmogorov published his results in 1941 [176].

A frequency-hopping modulation enables a narrowband system to operate over a wider bandwidth by changing the carrier frequency as a function of time. A variety of versions of frequency hopping were suggested over time, and the identity of original developer of frequency hopping is probably lost because of the secrecy surrounding this modulation approach. However, in what must be considered a relative unexpected source of contribution to communication modulation technology, a frequency hopping patent, was given to Austrian-born American actress Hedy Lamarr (filed as Hedy Kiesler Markey) and American composer George Antheil [208]. The technology exploited a piano roll as a key to select carrier frequencies of a frequency-hopping system.

As opposed to frequency hopping, direct-sequence spread spectrum (DSSS) modulates a relatively narrowband signal with a wideband sequence. The receiver, knowing this sequence, is able to recover the original narrowband signal. This technology is exploited by code-division multiple-access (CDMA) approaches to enable the receiver to disentangle the signals sent from multiple users at the same time and frequency. The origins of direct-sequence spread spectrum are partly a question of semantics. An early German patent was given to German engineers Paul Kotowski and Kurt Dannehl for a communications approach that modulated voice with a rotating generator [278]. This approach has a loose similarity to the digital spreading techniques used by modern communication systems. In the early 1950s, for direct-sequence spread-spectrum communications, the noise modulation and correlation (NOMAC) system was developed and demonstrated at Massachusetts Institute of Technology Lincoln Laboratory [338]. In 1952, the first tests of the communication system were performed. The system drew heavily from the doctoral dissertation of American engineer Paul Eliot Green, Jr. [338], who was one of the significant contributors to the NOMAC system at Lincoln Laboratory. Because direct-sequence spread-spectrum systems are spread over a relatively wide bandwidth, they can temporally resolve multipath more easily. Consequently, the received signal can suffer from intersymbol interference. To compensate for this effect, in 1958, the concept of the rake receiver, developed by American engineers Robert Price and Paul Eliot Green, Jr. [254, 338], implemented channel equalization. During late 1950s, the ARC-50 radio was designed and tested [278]. Magnavox's ARC-50 was an operational radio that is recognizable as a modern direct-sequence spread-spectrum system.

1.4 Television broadcast

While television technology is not a focus of this text, its importance in the development of wireless technology cannot be ignored. Given the initial success of wireless data and then voice radio communications, it didn't take long for researchers to investigate the transmission of images. Because of the significant increase in the amount of information in a video image compared to voice, it took decades for a viable system to be developed. Early systems often involved mechanically scanning devices.

German engineers Max Dieckmann and Rudolf Hell patented [81] an electrically scanning tube receiver that is recognizable in concept to televisions used for the following seventy years. Apparently, they had difficulty developing their concept to the point of demonstration.

Largely self-taught, American engineer Philo Taylor Farnsworth, developed concepts for the first electronically scanning television receiver ("image dissector") that he conceived as a teenager and for which he filed a patent several years later in 1927 [91]. In 1927, he also demonstrated the effectiveness of his approach.

During a similar period of time, while working for Westinghouse Laboratories, Russian-born American engineer Vladimir K. Zworykin filed a patent in 1923 for his version of a tube-based receiver [365]. However, the U.S. Patent Office awarded primacy of the technology to Farnsworth. In 1939, RCA, the company for which Zworykin worked, demonstrated a television at the New York World's Fair. Regular broadcasts soon began; these are often cited as the beginning of the modern television broadcast era.

1.5 Modern communications advances

In the modern age of wireless communications, with a few notable exceptions, it is more difficult to associate particular individuals with significant advances. During this era, communications systems have become so complicated that large numbers of individuals contribute to any given radio. It is sometimes easier to identify individuals who made significant theoretical contributions. However, so many significant contributions have been made that here only a small subset of contributions are identified that are particularly salient to the discussions found in the text.

While satellite communications are clearly wireless communications, this type of communication is not emphasized in this text. Nonetheless, the importance of satellite communications should not be underestimated. The first communication satellite, launched in 1958, was named signal communications orbit relay equipment (SCORE) [74]. It was developed under an Advanced Research Projects Agency (ARPA later renamed Defense ARPA or DARPA) program and demonstrated the viability of these satellites. It used both prerecorded and receive-and-forward messages that were broadcast on a shortwave signal.

Italian-born American engineer Andrew James Viterbi made numerous contributions to wireless communications. However, his most famous contribution is the development in 1967 of what is now called the Viterbi algorithm [327].

This algorithm specified the decoding of convolutional codes via a dynamical program approach that tracks the most likely sequences of states. In some ways, this development marked the beginning of the modern era of communications. Both in terms of the improvement in receiver performance and the computational requirements for the receiver, this is a modern algorithm.

From the time of Golay and Hamming, coding theory steadily advanced. By the end of the 1980s, coding had reached a point of diminishing returns. Over time, advances slowed and the focus of research was placed on implementations. However, coding research was reinvigorated in 1993 by the development of turbo codes by French engineers Claude Berrou and Alain Glavieux, and Thai engineer Punya Thitimajshima [19]. The principal contribution of these codes is that they enabled an iterative receiver that significantly improved performance.

One of the defining moments of the modern era was in 1973 when American engineer Martin Cooper placed the first mobile phone call. His team at Motorola was the first to develop and integrate their wireless cellular phone system into the wired phone network [63]. It is somewhat amusing that Cooper's first phone call was made to a competing group of cellular engineers at Bell Laboratories.

While numerous researchers contributed significantly to this area of investigation, the Spanish-born American engineer Sergio Verdu is typically identified as principal developer of multiuser detection (MUD) [322]. In systems in which multiple users are transmitting signals at the same time and frequency, under certain conditions, a receiver, even with a single receive antenna, can disentangle the multiple transmitted signals by exploiting the structural differences in the waveforms of the various signals. Because of the computational complexity and potential system advances of multiuser detection, this is a quintessentially modern communications concept.

Numerous researchers suggested multiple-antenna communications systems in a variety of contexts. These suggestions are both in the context of multiple antennas at either receiver or transmitter, and in terms of multiuser systems. For example multiple-input multiple-output (MIMO) systems were suggested by American engineers Jack H. Winters, Jack Salz, and Richard D. Gitlin [350, 351], and by Indian-born American engineers Arogyaswami J. Paulraj and Thomas Kailath [245]. Because he developed an entire system concept, the initial development of MIMO communications concepts is typically attributed to the American engineer Gerard Joseph Foschini who, in his 1996 paper [99], described a multiple-transmit and multiple-receive antenna communication system. In this system, the data were encoded across the transmit antennas, and the receiver disentangled these signals from the multiple transmit antennas.

In order to exploit MIMO communications links, some sort of mapping from the information bits to the baseband signal must be used. These mappings are typically called space-time codes. The trivial approach employs a standard single-antenna modulation and then demultiplexes these signals among the multiple transmit antennas. However, this approach suffers from poor performance because the required signal-to-noise ratio (SNR) is set by the SNR from the transmitter with the weakest propagation. The most basic concept for an effective space-time code is the Alamouti block code. This code, patented by Iranian-born American engineers Siavash M. Alamouti and Vahid Tarokh [7], is described in Reference [8]. Tarokh and his colleagues extended these concepts to include larger space-time block codes [305] and space-time trellis codes [307].

1.5.1 Early packet-radio networks

The ALOHA system (also known as ALOHAnet), which was developed by Norman Abramson and colleagues at the University of Hawaii beginning in 1968 [3], was one of the first modern wireless networks. The system involved packet radio transmissions using transceivers distributed on several islands in Hawaii. The underlying communication protocol used in ALOHAnet is now commonly known as the ALOHA protocol. The ALOHA protocol uses a simple and elegant random-access technique well-suited to packet communications systems. This protocol is described in more detail in Section 15.2. ALOHAnet was operated in a star network configuration, where a central station routed packets from source to destination terminals.

Ad hoc wireless networks, which are networks with no centralized control, received attention from the United States Department of Defense (DoD) starting in the early 1970s. The DoD was interested in such networks for their battlefield survivability and the reduced infrastructure requirements in battlefields, among other factors [103]. Through ARPA, the DoD developed several packet radio communications systems such as the packet radio network (PRNet), whose development began in 1972 [103]. This network was followed by a packet radio communication system for computer communications networks in San Francisco in 1975. RADIONET, as it was called [169], differed from ALOHAnet in that it had distributed control of the network management functions and used repeaters for added reliablity and increased coverage. Another notable feature of RADIONET is its use of spread-spectrum signaling to improve robustness against jamming. RADIONET was followed by several different efforts by DARPA through the 1970s and early 1980s to develop ad hoc wireless networks for military use. Notable among these is the low-cost packet radio (LPR) system, which was an outcome of DARPA's Survivable Radio Networks (SURAN) program. LPR used digitally controlled spread-spectrum radios with packet switching operations implemented on an Intel 8086 microprocessor [103].

Another important development in the history of wireless networks is the development of the wired Ethernet protocol by Robert Metcalfe and colleagues at the Xerox Palo Alto Research Center (PARC) in the early to mid 1970s [214]. Ethernet used carrier-sense-multiple-access (CSMA) technology (described in more detail in Section 15.3) and by 1981 offered packet data communication rates of 10 Mbps in commercially available systems at relatively low cost. In contrast, wireless packet networks offered data rates of only a few thousand bits per second at reasonable costs and equipment size. The enormous data rates offered by

Ethernet at low cost perhaps reduced the interest in developing wireless networking technologies for commercial use.

Interest in wireless networks for commercial use increased after the U.S. Federal Communications Consortium (FCC) established the industrial, scientific, and medical (ISM) frequency bands for unlicensed use in the United States in 1985. The ISM bands are defined in Section 15.247 of the Federal Communications Consortium rules. The freeing of a portion of the electromagnetic spectrum for unlicensed use sparked a renewed interest in developing wireless networking protocols [103].

Other major developments in the late 1980s and 1990s that increased interest in wireless networks were the increased use of portable computers, the internet, and significant reduction in hardware costs. Since portable computer users wanted to access the internet and remain portable, wireless networking became essential.

1.5.2 Wireless local-area networks

In 1997, what may be considered that grand experiment in wireless communications was initiated. The standard IEEE 802.11 [150] or WiFi was finalized for use in the industrial, scientific, and medical frequency band. While wireless communications were available previously, WiFi established a standard that enabled moderately high data rates that could be integrated into interoperable devices. This personal local-area wireless networking standard allowed individuals to setup their own networks with relative ease at a moderate price. Over the years, a number of extensions to the original standard have been developed. Of particular interest is the development of IEEE 802.11n that was finalized in 2009 [151] (although many systems were developed using earlier drafts). This provided a standard for WiFi multiple-input multiple-output (MIMO) wireless communications.

The IEEE 802.11 family of standards marked a turning point in the development of wireless networks as they were instrumental in making wireless local-area networks (W-LAN) ubiquitous throughout the world. Wireless LANs running some version of the IEEE 802.11 protocol have become so common that the term "WiFi," commonly used to signify compatibility with the 802.11 standard, made its debut in the Webster's New College Dictionary in 2005 [213].

Almost in parallel with the development of the IEEE 802.11 protocols, the European Telecommunications Standards Institute (ETSI) developed its own protocol for wireless networking called the HiperLAN (High Performance Radio LAN). HiperLAN/1 offered in excess of 20 Mb/s data transfer rate and thus had significantly higher data transmission rates than the existing IEEE 802.11 standard at the time [66]. The IEEE 802.11 standard incorporated a number of technical extensions that were both a good match to the computational capabilities of the time and provided paths to higher data rates in IEEE 802.11g. Over time, the HiperLAN standard lost market share to the IEEE 802.11 standards.