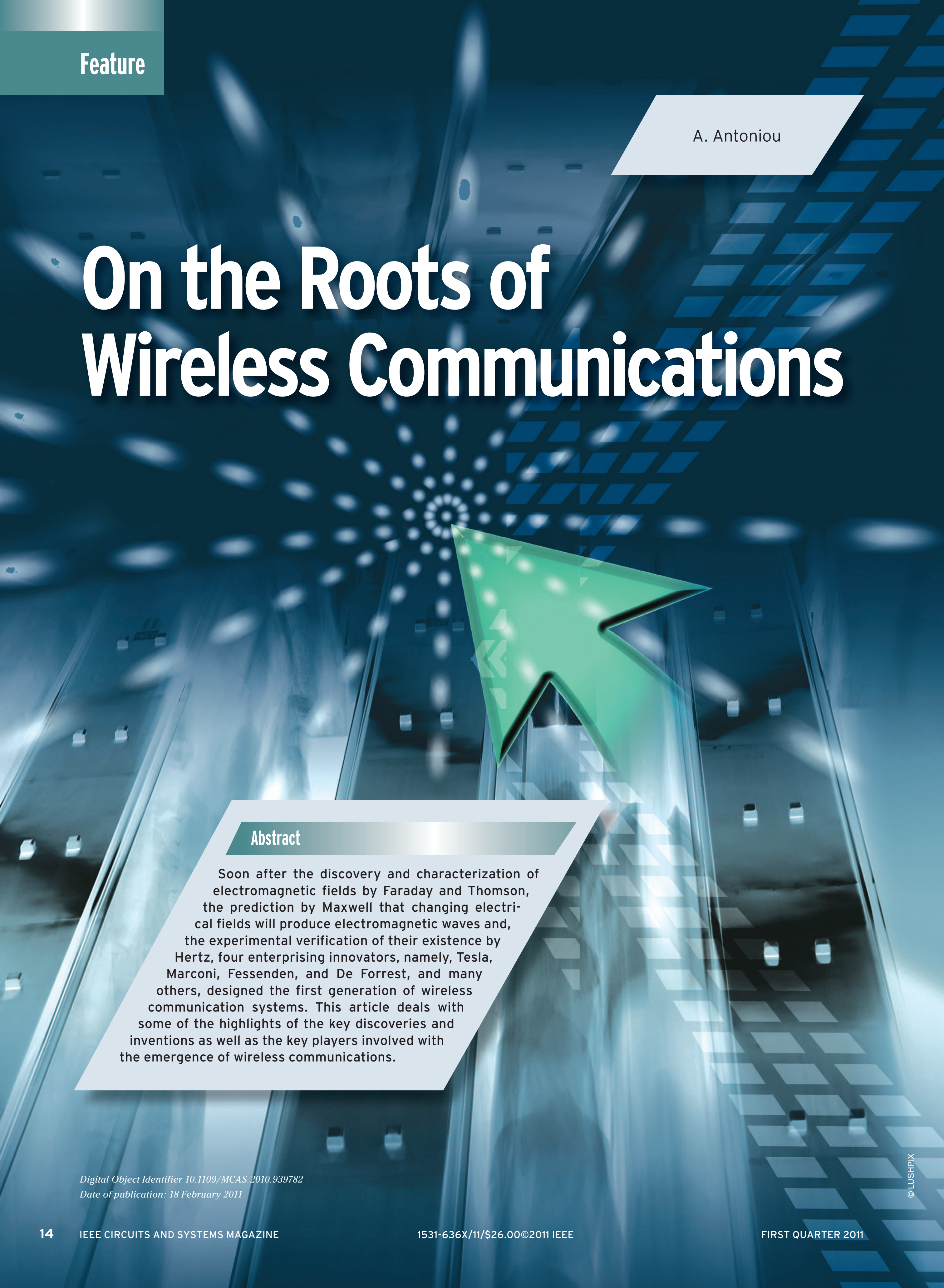
Feature

A. Antoniou

On the Roots of Wireless Communications



© LUSHPIX

Abstract

Soon after the discovery and characterization of electromagnetic fields by Faraday and Thomson, the prediction by Maxwell that changing electrical fields will produce electromagnetic waves and, the experimental verification of their existence by Hertz, four enterprising innovators, namely, Tesla, Marconi, Fessenden, and De Forrest, and many others, designed the first generation of wireless communication systems. This article deals with some of the highlights of the key discoveries and inventions as well as the key players involved with the emergence of wireless communications.

Digital Object Identifier 10.1109/MCAS.2010.939782
Date of publication: 18 February 2011

I. Introduction

From the beginning of civilization, man has attempted to communicate with fellow man over long distances. Pigeons were used in ancient Greece to send messages such as the outcomes of the Olympic Games going back to the eighth century BC. The kings of Persia ruled their empire through a relay system of horseback couriers. According to the great historian Herodotus, these couriers could deliver messages over a distance of 1600 miles in just nine days. In another part of his histories, describing the advance of the Persian army in 480 BC by land and sea towards Athens, having crossed the Hellespont,[1] Herodotus recounts that "When the Greeks stationed at Artemisium learned what had happened by *fire signals* from Skiathus, they were terrified and retreated to Chalcis so that they could guard the Euripus strait" [1] (see Google Earth map in Fig. 1).

The rapid advancements made in understanding the properties of electricity during the 1800s motivated many scientists, engineers, and innovators to explore the application of electricity in numerous and diverse areas of endeavor. Many of these pioneers began to explore the design and construction of wired and wireless telegraph systems and eventually the design of wireless voice communications.

This article deals with some of the highlights of the key discoveries and inventions that led to what we call today *wireless communications.* The people involved, who can legitimately be called the *fathers of wireless communications,* can be divided into two groups: the *discoverers* and the *inventors.*

[1]Narrow strait between Asia and Europe known nowadays as the Dardanelles.

II. The Discoverers

The key scientific discoveries that led to wireless communications were made by

- Michael Faraday (1791–1867)
- William Thomson (Lord Kelvin) (1824–1907)
- James Clerk Maxwell (1831–1879)
- Heinrich Rudolf Hertz (1857–1894)

Michael Faraday's formal education came to an abrupt end when he was thirteen years old under rather unfortunate circumstances. According to the record, Michael had a speech impediment associated with the pronunciation of 'r': he had what is sometimes referred to as a soft 'r' whereby he would refer to his older brother Robert as

Figure 1. Persian invasion of Greece.

A. Antoniou is a Life Fellow IEEE; he is Emeritus professor with the Department of Electrical and Computer Engineering, University of Victoria, Victoria, B.C., CANADA, V8W 3P6, Email: aantoniou@ieee.org.

Faraday meticulously explored many chemical and physical phenomena and before too long, he became the consummate experimentalist and an authority on electrical and other physical phenomena.

'Wobert' and whenever he was asked to give his name he would reply 'Mike' so as to avoid saying 'Fawaday'. Had he lived in the twentieth century, he would refer to Bucks Bunny as that 'Wascal Wabbit'. Determined to correct Michael's speech impediment using the allowable means of the time, his teacher gave Michael a thrashing of such severity that caused Michael's mother to remove him, as well as his brother Robert, from school neither to return to formal education again [2] [3] [4]. Michael was soon hired as an errand boy by a certain French emigré by the name of George Riebau who ran a bookbinder's/bookseller's shop only a few minutes walk from Piccadilly Circus London, UK. Within a year or so, Riebau recognized the potential of young Michael and offered him a bookbinder's apprenticeship. This turned out to be Michael's university. Having learned how to read and write during the course of his limited formal education, he would devour any book that came in for binding and he frequently attended lectures by famous scientists at the Royal Institution also a few minutes walk from Piccadilly Circus. Faraday's break in life came about when a very famous chemist and inventor of the 1800s by the name of Humphry Davy appointed him in 1813 as his chemical assistant at the Royal Institution,[2] having read the meticulous notes that Faraday produced of Davy's own lectures.

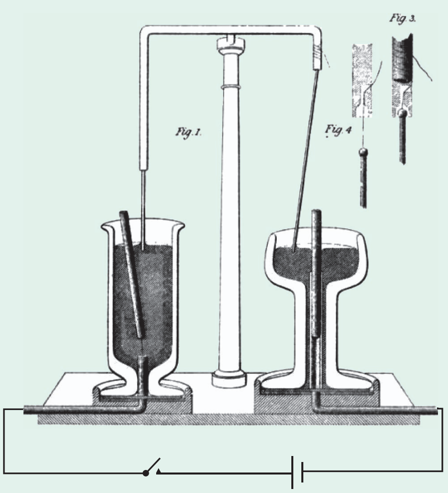


Figure 2. Faraday's electromagnetic rotator (see [7]).

[2]The Royal Institution continues to flourish today as a science center and museum featuring the work of Faraday and many other scientists who worked there.

Faraday's duties were many and diverse and included assisting Davy by performing experiments and demonstrations related to his investigations and lectures and also doubled as his personal assistant on occasion. Faraday meticulously explored many chemical and physical phenomena and before too long, he became the consummate experimentalist and an authority on electrical and other physical phenomena.

Davy's claim to fame was his discovery of nitrous oxide (laughing gas), sodium, and potassium, his work on chlorine and iodine, and his invention of the miner's safety lamp.

Later on, having gained a measure of independence from Davy, Faraday began to study the properties of electricity and magnetism for the Royal Institution where he worked. In 1821, he demonstrated that a relationship exists between electric current and magnetism, namely, *Faraday's law* [5] [6]. To demonstrate and publicize his theory, he constructed a so-called *rotator* and although nothing more than a toy, it was essentially the first induction motor. This great discovery, as reported by Faraday himself in [5], is illustrated in Fig. 2 [7] with a modern DC source in series with a switch connected to the two terminals of the device. It consisted of two suitably shaped glass vessels containing mercury, 2 rod magnets, a bridge made of metal, a nonconducting stand, and some copper wire. With the switch closed, current would flow through the left vessel, up through the conducting bridge, and down through the right vessel. To his delight, Faraday noticed that the left rod magnet was rotating counterclockwise as viewed from above according to, well, Faraday's law. On the basis of the same principle, the right rod magnet would rotate clockwise but as it was fixed to the glass vessel, the dangling wire rotated in the counterclockwise direction by virtue of Newton's third law of motion about action and reaction.

Ten years later, in 1831, Faraday discovered that a changing current in a coil wound on an iron ring would induce a current in another coil wound on the same iron ring, which is the basis of the *transformer* [8]. Faraday's original transformer is illustrated in Fig. 3 and is currently an exhibit at the museum of the Royal Institution [9].

Faraday remained the ultimate experimentalist for the rest of his life and in due course he would emerge

Figure 3. Faraday's induction ring (see [9]).

Figure 4. Cartoon from the *Punch* issue of 21 July 1855 (see [7]).

as an important political figure of the Victorian times. He got himself involved with issues ranging from the education system in England to environmental issues like the pollution of river Thames. In regards to education, he lobbied for increased scientific content in the secondary-level curriculum and the strengthening of teaching at postsecondary institutions. On the other hand, to publicize the unfortunate state of river Thames, he once wrote a public letter to the *Times* expressing his outrage. In support of his stand, he would perform impromptu demonstrations to publicize the great calamity. He would throw small white cards into the river which would instantly disappear in the murky water! (See Fig. 4 for a relevant cartoon that appeared in *Punch* in 1855; see [2] [3] [7] for additional information.)

A few years after Faraday's discoveries, a 21-year-old mathematics graduate from Cambridge University by the name of William Thomson read Faraday's paper *Experimental Researches in Electricity* [8] and was surprised to find no equations in it. During the early 1840s he stumbled on the work of Fourier on the properties of heat (Analytical Theory of Heat) and around 1845 he formulated an analogy between heat and electrical phenomena and was thus able to show that certain equations proposed by Fourier pertaining to heat phenomena could also quantify the properties of Faraday's hypothetical lines of force around an electrically charged object. During the 1850s and 1860s he made numerous scientific contributions pertaining to the design, laying, operation, and maintenance of the first transatlantic telegraph cables as the main scientific consultant for these projects. His contributions include a paper arguing that the speed of the signal through a given cable core is inversely proportional to the square of the length of the cable, a classical modern bandwidth issue, and recommended a wider cross-section for the core and the insulation of the cable [10]. He was knighted by Queen Victoria for this work and adopted the title Lord Kelvin. He is forever linked to the unit for absolute temperature, degrees Kelvin, for developing the basis for absolute zero.

In due course, Thomson emerged as an innovator cum business man and acquired wealth and fame but steadfastly held to some of his early beliefs about science. Not knowing that there are other sources of heat beyond the heat possessed by the earth at the time of its formation, he argued for many years that the earth could not be older than 10 million years, 100 million maximum. On the other hand, he never fully accepted the notion of the electron as proposed by J. J. Thomson (no relation) in 1897. (See [11] and [12] for additional information.)

The work of Thomson on the properties of electricity was continued by James Clerk Maxwell who was another young mathematics graduate from Cambridge University and who was also acquainted with Faraday and Thomson both personally and professionally. Before too long, he extended the mathematical formulation of Thomson on Faraday's hypothetical magnetic lines of force and in 1855 and 1856 he delivered a two-part paper to the Cambridge Philosophical Society on

Maxwell eventually deduced his equations through the sheer force of mathematics without relying on his initial mechanical model.

his results [13]. His work was later published in [14]. He showed that the behavior of electric and magnetic fields and their interactions can be fully quantified by several pages of equations. A most interesting aspect about these equations is the way Maxwell set about to discover them. He formulated an analogous mechanical system in his mind, whose dynamic properties corresponded one for one to all the known properties of electricity. He imagined that the space occupied by a current-conducting material was also filled with tiny spherical spinning flexible cells and between these tiny spherical cells there were even tinier spherical cells that could transmit motion among the neighboring bigger cells. In effect, it seems that he had set up an imaginary analog computer in his mind which could account for all the known electrical effects. Bothered about the physical nature of the two kinds of tiny spherical cells, Maxwell eventually deduced his equations through the sheer force of mathematics without relying on his initial mechanical model. Further work revealed that a changing magnetic field would produce an electromagnetic wave and in 1862 Maxwell showed that the speed of propagation of such a wave would be approximately the same as the speed of light. He also predicted that a relation must exist between light, on the one hand, and electric and magnetic phenomena on the other.

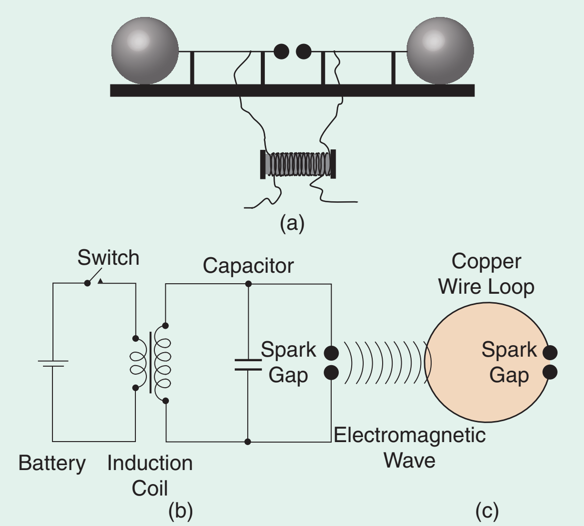


Figure 5. Experimental setup of Hertz: (a) Actual set up (b) modern schematic of transmitter, (c) receiver.

The compact form of Maxwell's equations we know today was introduced by Heaviside [15] using vector calculus which emerged during the late 1800s. Like Faraday, Heaviside was a self-taught electrical engineer but unlike Faraday, he achieved great heights in mathematics.

Maxwell made several other less known contributions to science in his early career. He proposed the *Maxwell color triangle* whereby each vertex of an equilateral triangle represents one of the three primary colors, red, blue, and green, and every point inside the triangle represents a color whose color components are in the proportions of the lengths of the perpendiculars drawn from that point to the three sides of the equilateral triangle. He also studied a subject that would be very familiar to the circuits and systems researchers of today. *Centrifugal governors* were used throughout the 1800s to regulate the speed of steam engines. This is one of the earliest *feedback systems*, if not the earliest, and as such it was subject to stability issues. Maxwell formulated dynamic equations that would stabilize a centrifugal governor.

In 1871, Maxwell was appointed as the founding director of the famous Cavendish Laboratory at the University of Cambridge, which was the home of many scientific discoveries including the electron. Unfortunately for science, he died at the age of 48 due to illness. (See [13] [16] [17] for additional information.)

The work of Maxwell on the relationship between light and electromagnetic waves was continued by Heirich Rudolf Hertz who received a PhD degree in physics from the University of Berlin in 1880 having studied under the supervision of Gustav Kirchhoff. In 1885, at the age of 28, Hertz was appointed professor of physics at Karlsruhe University. In 1887, Hertz demonstrated by experiment that electricity can be transmitted by electromagnetic waves *which travel at the speed of light* and which possess many of the properties of light, e.g., reflection and refraction, thus verifying Maxwell's predictions. His experimental set-up comprised a *transmitter* made up from an induction coil, two large metal spheres which served as a capacitor, and a spark-gap mechanism, as illustrated in Fig. 5a. The induction coil and metal spheres served, in effect, as a crude *parallel resonant circuit*, as shown in Fig. 5b, which produced a damped sinusoidal oscillation. The parallel resonant circuit became an indispensable component of future transmitters. He also constructed a *receiver* using a loop of copper wire and a spark-gap mechanism similar to that of the transmitter, as shown in Fig. 5c.

Like lightning, a strong spark at the spark gap of the transmitter would produce an electrical disturbance which would, in turn, induce some current in the receiving copper loop but probably not sufficiently strong to produce an observable spark. By patiently selecting the size of the spheres and adjusting the distance between them and the widths of the two spark gaps, Hertz was able to *tune* the transmitter and receiver so as to obtain an observable spark at the receiver. It helped, of course, to perform the experiment in a dark room and also use a magnifying glass to observe the fleeting spark!

Hertz's students were impressed and asked what this marvelous phenomenon might be used for. "This is just an experiment that proves that Maxwell was right, we just have these mysterious electromagnetic waves that we cannot see with the naked eye. But they are there." "So, what next?" asked one of his students. Hertz shrugged. A modest man of no pretensions, he replied, "Nothing, I guess." He moved on to other research projects in the fields of contact mechanics and electrodynamics. Like Maxwell, he died due to illness at the early age of 36. (See [18] for additional information.)

Maxwell's equations remained largely obscure for many years but after the experimental verification of the existence of electromagnetic waves by Hertz, interest began to grow by leaps and bounds. Nevertheless, to the end of his life, Thomson was unable to accept the true nature of electromagnetic waves. He believed that space is occupied by ether and that electromagnetic waves are mechanical properties of the ether. Consequently, the true equations pertaining to electromagnetic waves should involve the mechanical constants of ether in some way. On the other extreme, Einstein described in more recent times Maxwell's work as the "most profound and the most fruitful that physics has experienced since the time of Newton".

III. The Innovators

Following the verification of Maxwell's predictions by Hertz, a group of illustrious innovators appeared on the scene determined to exploit the newfound knowledge. There were many such individuals but four of them, namely,

- Nikola Tesla (1856–1943),
- Guglielmo Marconi (1874–1937),
- Reginal Aubrey Fessenden (1866–1932), and
- Lee De Forest (1873–1961)

left a substantial legacy.

Nikola Tesla was a Serbian who emigrated to the US early in 1884 at the age of 28. He dedicated his life to the generation, transmission, and utilization of electrical energy. He invented single-phase and multi-phase alternators and induction motors. AC current was chosen for power generation and transmission from the start only because Tesla's AC system won over Edison's DC system.[3] In 1881, he invented the *Tesla coil*, illustrated in Fig. 6, which he used to generate spectacular sparks for the amazement of everybody and which was to be used soon after as a crucial component in many of the early wireless transmitters.

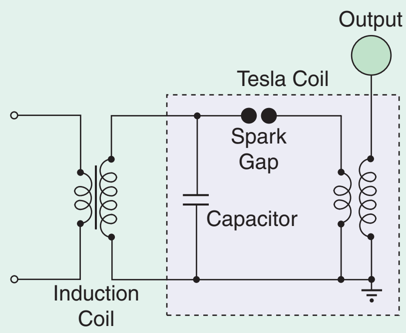


Figure 6. The Tesla coil.

The quest of his life was to transmit electrical energy, huge amounts, over wireless systems. In this respect, he filed a patent for a wireless system for the transmission of electrical energy on September 2, 1897, which was eventually granted by the US Patent Office in 1900 (see [19]). The system comprised a transmitter, basically a step-up transformer driven by an alternator, and a receiver, basically a step-down transformer loaded by a series of lights and motors connected in parallel, as shown in Fig. 7a. The modern schematic of the sytem is shown in Fig. 7b. When the winding stray capacitances are added, as illustrated in Fig. 7c, the primaries and secondaries of the transformers at the transmitter and receiver would each operate as a coupled tuned circuit. For this reason, the wireless system came to be known as Tesla's *system of four tuned circuits.* The transmitter and receiver were, in effect, *bandpass filters*, the first equipped with a transmitting antenna and the second equipped with a receiving antenna.

Tesla died of heart failure and in debt in a New York hotel room he used to call home, having sold his many patents in previous years. He failed to fulfil his great ambition, namely, to transmit large amounts of power through wireless systems. (See [20] [21] for additional information.)

Inspired by the work of Hertz, Guglielmo Marconi began experimenting with spark transmitters in the attic of the family home in Pontecchio, near Venice, while still a teenager. He explored ingenious ways that would increase the distance over which effective

[3]A key decision in favor of AC power generation and transmission was made in 1883 by an international commission, headed by Thomson (Lord Kelvin by that time), to decide on the design of the power station at Niagara Falls [12].

Inspired by the work of Hertz, Guglielmo Marconi began experimenting with spark transmitters in the attic of the family home in Pontecchio, near Venice, while still a teenager.

transmission could be achieved. Soon he was able to transmit signals over an impressive distance of about 1.5 km. At the age of 21, Marconi traveled to London with his wireless system determined to make his fortune. While in London, he gained the attention of a certain William Preece, Chief Electrical Engineer of the British Post Office (now British Telecom). In a landmark presentation on December 2, 1896, Preece demonstrated Marconi's invention. When a lever was operated at the transmitting box, a bell was caused to ring in the receiving box across the room, the first *remote control*. Through a series of demonstrations, Marconi transmitted signals of Morse code over a distance of 6 km and after that 16 km. In due course, he was able to send Morse signals over the Atlantic. Marconi was a smart system designer and a clever entrepreneur who would readily adopt and modify ideas reported by his peers. He used a so-called *Righi oscillator*, a device known as a *coherer* invented by Branly and improved by Lodge, an aerial system of Dolbear, and Tesla's coil. (See [22] [23] [24] for more information.)

A typical spark-gap wireless system used by Marconi and others during the late 1890s and early 1900s is illustrated in Fig. 8a. Basically, the transmitter consisted of an induction coil in series with a relay, a parallel resonant circuit, and a spark gap constructed from two metal balls similar to those used by Hertz. When the Morse key was depressed, a voltage was induced in the primary as well as the secondary of the induction coil and a spark was initiated at the spark gap. The electromagnetic field of the primary opened the relay switch which interrupted the current but when the field collapsed, the relay was reset and if the Morse key was kept depressed a second cycle would begin. Thus as long as the Morse key was kept depressed, a series of dumped oscillations of the type shown in Fig. 8b was generated in the loop of the secondary thereby sustaining a continuous oscillation at the resonant frequency. The early receivers comprised two circuits, the antenna circuit and the Morse sounder circuit. The antenna circuit comprised a coil, a battery, a relay, and a *coherer*, as shown in Fig. 9a. The coherer was a glass tube with metal filings sandwiched between two small metal pistons as shown in Fig. 9b.

When a high-frequency current passed through a coherer, the metal filings would tend to stick to each other through a so-called *micro-weld phenomenon*, and the resistance of the coherer would assume a low value. Thus, the battery in the antenna circuit would supply enough current to activate the relay. The relay would then close the switch in the sounder circuit which would activate the Morse sounder to produce the characteristic Morse click.

The Morse sounder circuit comprised a battery and a *decoherer* which was essentially an electrically activated knocker. As a budding electrical engineer would

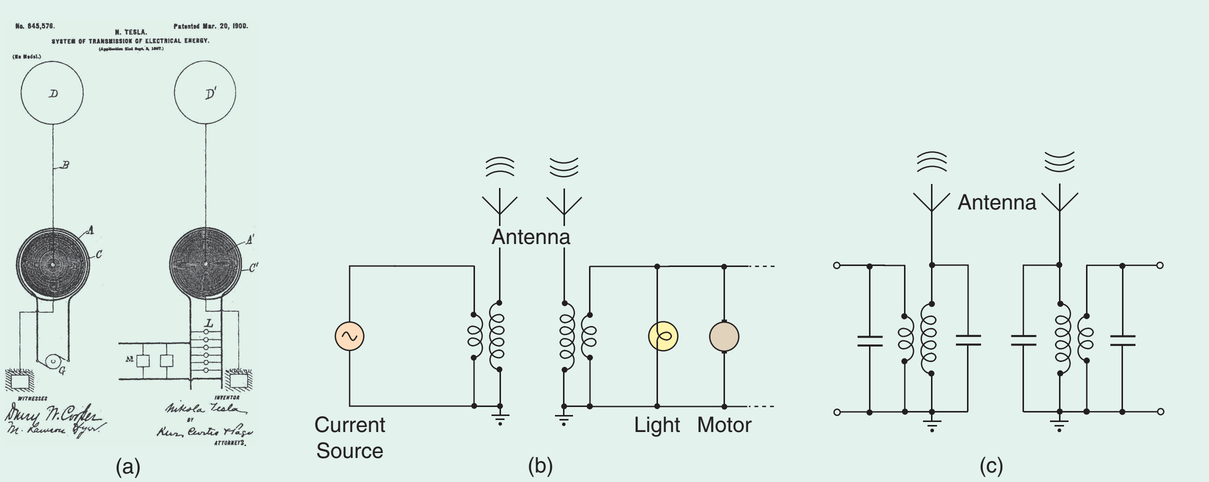


Figure 7. Tesla's wireless system: (a) Patent schematic [19], (b) modern schematic, (c) modern schematic with stray capacitances.

From the start, the pioneers of the time realized that the higher the voltage of the transmitter source and the taller the antenna tower, the farther the electromagnetic wave would travel.

no doubt know, once magnetized, iron filings tend to stick to each other due to the hysteresis effect and that caused the resistance of the coherer to remain low after the signal strength returned to zero. Consequently, it was soon found out that the coherer had to be reset to its initial state soon after the transmitted signal disappeared, and the low-tech technique of the time was to give the coherer a whack with a decoherer.

From the start, the pioneers of the time realized that the higher the voltage of the transmitter source and the taller the antenna tower, the farther the electromagnetic wave would travel, and to achieve more accurate transmission over larger distances, they began to use larger and larger voltages, eventually in the range of kilovolts. This imposed unusual requirements on the design of the components used. Just to put things into perspective, the vital statistics of some of the components used by Marconi in 1902 in his first North American telegraph station at Glace Bay, Nova Scotia, and the corresponding station across the Atlantic at Clifden, Ireland, should be mentioned. The transmitter voltage source comprised three 500-volt DC generators in series connected in parallel with a battery made up of 2000 2-volt batteries in series. On the other hand, the capacitor[4] comprised 1,800 sheets of metal each measuring 9 × 3.6 m (yes, meters) hanging 30 cm apart from the ceiling in a huge room specially constructed to house the capacitor (see pp. 395–397 of [23]).

A large voltage in the range of kilovolts would, of course, cause a huge current in the transmitter circuit. Interrupting such a current would cause a thunderous cracking noise accompanied by a spectacular flash. Essentially, the telegraph operators of the time were creating man-made thunders and lightnings which caused the telegraph stations of the time to resemble virtual 'Frankenstein houses', particularly at night.

With such high voltages and currents, a new problem soon arose. Once ignited, the spark across the gap was

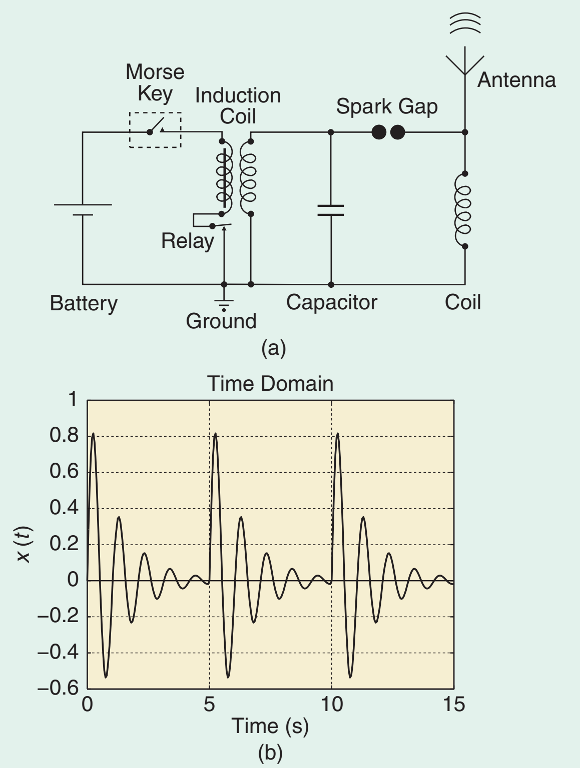


Figure 8. Early wireless transmitter: (a) Schematic, (b) typical transmitted signal.

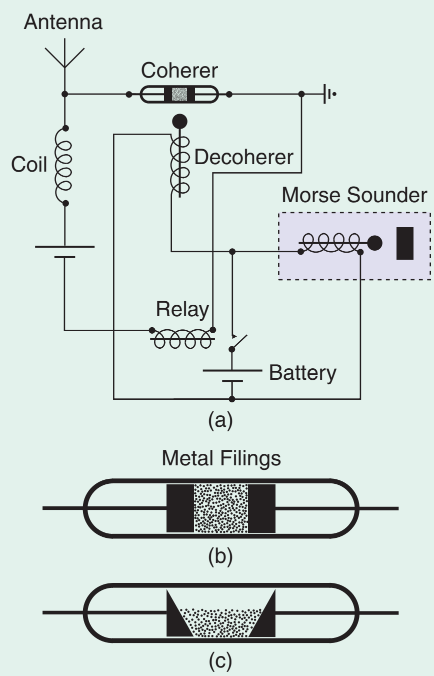


Figure 9. (a) Early wireless receiver, (b) coherer, (c) adjustable coherer.

[4]Known as a *condenser* in those days.

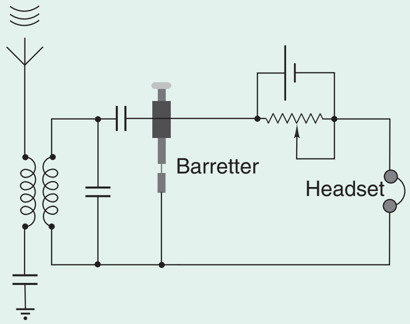


Figure 10. Fessenden's hot-wire barretter receiver.

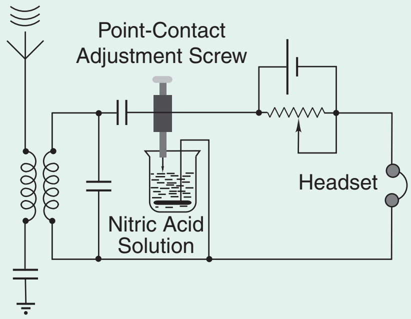


Figure 11. Fessenden's electrolytic receiver.

difficult to extinguish. A solution attributed to one of Marconi's consultants, namely, Professor John Ambrose Fleming, was to use a spark rotator which was essentially a motor-driven disk rotating through the spark gap at right angles to the current flow [23]. The disk was equipped with conducting studs uniformly distributed around its periphery. As each stud passed through the spark gap, the spark would be ignited but it would soon be extinguished as the stud moved away from the spark gap.

Fleming also invented the vacuum-tube diode in 1904 and made many other contributions to electronics, communications, and radar. He was knighted in 1929 and was awarded the IRE[5] Medal of Honor of 1933.

Improvements in the transmitter were accompanied by a series of equally noteworthy refinements in the receiver. Marconi designed a more efficient *adjustable* coherer. By using a slanted piston, as shown in Fig. 9c, the resistance of the column of filings could be increased or decreased by rotating the tube: a longer column of filings with reduced cross section would cause the resistance to increase; alternatively, a shorter column of filings with a larger cross section would cause the resistance to decrease. The coherer turned out to be a most temperamental device, as may be expected, and the wireless practitioners of the time explored all manner of things to replace it. Borrowing certain ideas from Rutherford, Marconi patented a magnetic receiver that relied on the demagnetizing effect of a dumped oscillation. Marconi received the IRE Medal of Honor of 1920.

Like Thomson, Marconi became rich and famous and spent the latter half of his life commuting between Europe and the USA doing business and socializing with the upper layers of the society.

During the early 1900s, a Canadian by the name of Reginald Aubrey Fessenden jumped into the arena of wireless communications. He started his technical career with Edison in 1886. Having occupied academic positions after 1890 at the University of Purdue and the Western University of Pennsylvania (today's University of Pittsburgh), he joined the US Weather Bureau in 1900 for the specific purpose of exploring the practicality of using a network of coastal telegraph radio stations to transmit weather information thereby eliminating the need of telegraph lines. Like Marconi, Fessenden considered the coherer an unreliable device and, in fact, according to the record, he considered it a misfortune that retarded the development of practical receivers. Consequently, while at the US Weather Bureau, Fessenden developed the so-called *hot-wire barretter*, shown in Fig. 10, which consisted of a minuscule piece of very fine platinum wire (length: 0.002", diameter: 0.0006") [25] mounted on a holding device. Platinum wire of such fine dimensions could be obtained by dissolving the silver coating in a kind of silver-coated platinum wire known as *Whollaston wire*, which was often used in electrical instruments in those days.

The operation of the hot-wire barretter relied on the heating of the platinum wire caused by the received signal. In the presence of a signal, the resistance of the barretter would increase and thus the current through the barretter would be reduced and, consequently, the current shunted to the headset would be increased by virtue of Kirchhoff's laws. In effect, the received signal would modulate the audio signal heard through the headset. In theory, it would be possible to use the device to detect *amplitude-modulated signals* although the practical difficulties would be numerous.

While experimenting with different hot-wire barretter designs immersed in a solution of nitric acid, essentially to dissolve the layer of silver of the Whollaston wire in order to expose the platinum core, Fessenden noticed that one design was much more efficient than all the others in detecting electromagnetic waves. On close examination, he found out that the platinum wire

[5]The Institute of Radio Engineers was one of the two predecessors of the IEEE.

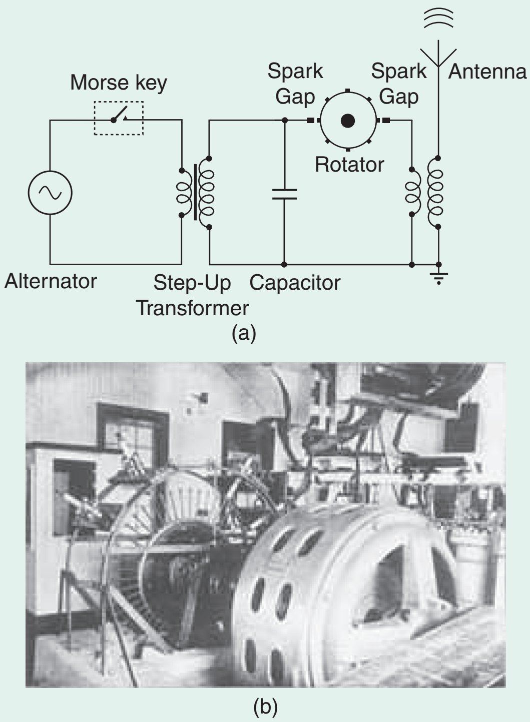


Figure 12. Fessenden's transatlantic transmitter (a) Schematic, (b) actual alternator used fitted with radial spark rotator (see [26]).

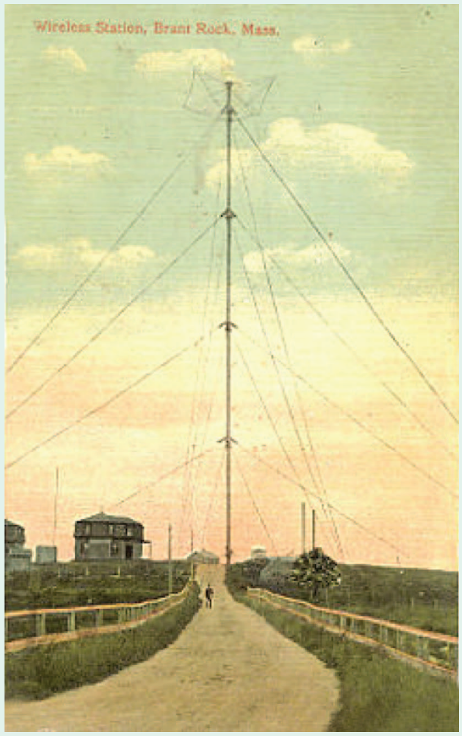


Figure 13. Fessenden's 128-meter antenna tower at Brant Rock (see [26]).

in the most efficient hot-wire barretter was *broken*! And thus the *electrolytic receiver* shown in Fig. 11 was invented. The two pieces of the broken filament acted like the anode and cathode of an electrolytic tank. If the anode in such a device is made positive, positive ions would tend to cling to the platinum wire, which would cause the resistance between anode and cathode to increase. A negative voltage, on the other hand, would tend to disperse the positive ions and thus the resistance would be decreased. With the electrolytic tank properly biased and tuned, an alternating voltage received by the antenna would tend to reduce the effective resistance and, consequently, a current *modulated* by the received signal would flow through the headset. The electrolytic barretter remained the detector of choice over several years.

In 1902, certain disputes concerning patent rights caused Fessenden to leave the US Weather Bureau. However, he soon teamed up with a couple of wealthy Pittsburgh businessmen who financed the formation of the National Electric Signaling Company. They decided to establish a commercial transatlantic radio telegraph service in direct competition with Marconi in 1906 between Brant Rock in the USA and Machrihanish at the west coast of Scotland. Both telegraph stations relied on a new transmitter that was using an alternator instead of a DC source and also a new type of radial spark rotator as illustrated in Fig. 12a. The capacitor and the induction coil formed a *parallel resonant circuit* and the induction coil essentially served as a *step-up radio-frequency transformer* as in many earlier transmitters. The alternator would produce two sparks per rotation, one for each half cycle, and to ensure that the sparking was synchronized with the waveform, Fessenden had the radial rotator mounted on the shaft of the alternator, as can be seen in Fig. 12b. The 128-meter antenna tower used at Brant Rock is illustrated in Fig. 13.

With this system, increased transmission frequencies could be achieved and, in this way, Fessenden was able to achieve two-way transatlantic transmission before Marconi although, according to the record, the transmitters could not bridge the Atlantic during daylight hours or during the summer months. Unfortunately, in December 1906, a defective joint caused the Machrihanish tower to collapse and that seems to have caused the enterprise to be terminated before it could go into commercial service.

Fessenden believed from the start that the way to the future was through the transmission of continuous waves. Consequently, he explored the use of

Fessenden believed from the start that the way to the future was through the transmission of continuous waves.

high-frequency alternators as the transmitter source including multi-phase alternators of the type invented by Tesla to increase the spark rate even more. By using a 125-Hz, 3-phase alternator, he was able to achieve a spark rate of 750 sparks per second. By this means, the typical short and long clicks of the early Morse signals would be replaced by the more familiar short and long audio tones. He also experimented with high-speed alternators operating at frequencies as high as 50 kHz, some say 100 kHz, and proposed the *heterodyne detector* but these innovations could not be effectively utilized at that time. Fessenden received the IRE Medal of Honor of 1921 for his contributions. (See [23] [26] for additional information.)

The real breakthrough to modern wireless communications had to wait for the emergence of power amplification. This took place in 1906 when an American inventor by the name of Lee De Forest[6] was to add another electrode to Fleming's vacuum-tube diode to invent the so-called *audion* as an amplifying device as illustrated in Fig. 14. He filed a US patent for the device in 1907 which was granted in 1908 [27]. Soon after the invention of the audion, De Forest is on the record as having broadcast the first ship-to-shore message announcing the results of a regatta that took place at that time in Lake Erie and is credited for broadcasting in 1910 a live performance from the Metropolitan Opera House in New York featuring Italian tenor Enrico Caruso. He continued to be involved with the evolution of radio during the next decade.

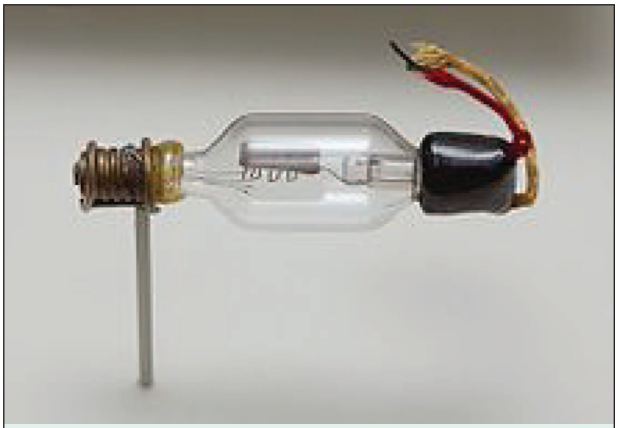


Figure 14. De Forest's audion (see [28]).

[6]Lee De Forest was educated at Yale University having received a bachelor's degree and a PhD in 1896 and 1899, respectively.

The audion was not actually a true vacuum tube in that it was partially filled with gas. In fact, De Forest thought that its operation was critically dependent on ions generated in the gas in the presence of an electric field. Further research on the device in later years showed that it would operate a lot better without the gas and, after further development, it emerged by 1919 as the vacuum-tube triode. Unlike the audion, the vacuum-tube triode could achieve linear amplification [28]. Soon after, the triode became the primary component of wireless communication systems.

In addition to the audion, De Forest invented in 1920 an early sound-on-film process, the so-called *Phonofilm process*. The circumstances associated with this process as well as his other inventions are both dramatic and controversial and would make a good story for a Hollywood feature movie.

In 1922 De Forest won the IRE Medal of Honor for his contributions to radio and in 1959 he received an Oscar *for his pioneering inventions which brought sound to the motion pictures*. He died relatively poor with just over one thousand dollars in his bank account. (See [29] [30] for additional information.)

The work of these early pioneers was continued by others, far too many to mention, throughout the twentieth century and continues unabated today. The vacuum-tube triode was followed by multi-electrode vacuum tubes, which were followed by a host of transistor types, which were then followed by the integrated circuit. Each technology, in its turn, revolutionized the state-of-the art of wireless communications and changed our way of life in the process for better or worse.

This article is based on a presentation at the International Workshop on Advances in Communications which was organized in honor of the distinguished career of Professor Vijay K. Bhargava on the occasion of his sixtieth birthday [31].

IV. Conclusions

Starting with a great deal of curiosity, Faraday showed by experiment that an electrical current in a conductor creates a magnetic field around the conductor. Thomson characterized the relation between the current and the magnetic field produced by equations. Through the power of mathematics, Maxwell predicted that a changing current in a conductor would produce a traveling electromagnetic wave with properties similar to those associated with light. Hertz verified by experiment that Maxwell was correct in his predictions about electromagnetic waves and moved on to other more interesting research projects. Tesla, Marconi, Fessenden, De Forest, and many others were able to design electrical circuits that could transmit information by means of electromagnetic waves over long distances and to receive and interpret the transmitted information, thus changing the way we live permanently.

Andreas Antoniou (M69-SM79-F82-LF04) received the B.Sc.(Eng.) and Ph.D. degrees in electrical engineering from the University of London in 1963 and 1966, respectively, he is a Life Fellow of the IEEE and Fellow of the IET. He taught at Concordia University from 1970 to 1983, was the founding Chair of the Department of Electrical and Computer Engineering, University of Victoria, B.C., Canada, from 1983 to 1990, and is now Professor Emeritus. His teaching and research interests are in the area of digital signal processing. He is the author of Digital Signal Processing: Signals, Systems, and Filters, McGraw-Hill, 2005 and the co-author with Wu-Sheng Lu of Practical Optimization: Algorithms and Engineering Applications, Springer, 2007.

Dr. Antoniou served as Associate/Chief Editor for IEEE Transactions on Circuits and Systems (CAS) from 1983 to 1987, as a Distinguished Lecturer of the IEEE Signal Processing and the Circuits and Systems Societies during 2003–2004 and 2006–2007, respectively, and as General Chair of the 2004 International Symposium on Circuits and Systems.

He was awarded the CAS Golden Jubilee Medal by the IEEE Circuits and Systems Society and the B.C. Science Council Chairmans Award for Career Achievement both in 2000, the Doctor Honoris Causa degree by the National Technical University, Athens, Greece, in 2002, the IEEE Circuits and Systems Society Technical Achievement Award for 2005, the IEEE Canada Outstanding Engineering Educator Silver Medal for 2008, and the IEEE Circuits and Systems Society Education Award for 2009.

References

[1] R. Waterfield, Herodotus, *The Histories. London*, U.K.: Oxford Univ. Press, 1998, ch. 7, art. 183, p. 469.

[2] A. Hirshfeld, *The Electric Life of Michael Faraday. Walker*, 2006.

[3] A. Hamilton, *A Life of Discovery*. New York: Random House, 2002.

[4] Michael Faraday [Online]. Available: http://www.ilt.columbia.edu/projects/bluetelephone/html/faraday.html

[5] M. Faraday, "Historical sketch of electromagnetism," *Ann. Philos*., vol. 2, pp. 195–200, 274–290, 1821.

[6] M. Faraday, "Historical sketch of electromagnetism," *Ann. Philos*., vol. 3, pp. 107–121, 1821.

[7] Michael Faraday [Online]. Available: http://en.wikipedia.org/wiki/Michael_Faraday

[8] M. Faraday, "Experimental researches in electricity," *Philos. Trans. Roy. Soc. Lond*., vol. 122, pp. 126–162, 1821.

[9] Faraday's Induction Ring [Online]. Available: http://www.rigb.org/contentControl?action=displayContent&id=00000000024

[10] W. Thomson, "On the theory of the electric telegraph," *Math. Phys. Pap*., vol. 2, p. 61, 1854.

[11] D. Lindley, "Degrees Kelvin," *Math. Phys. Pap*., vol. 2, p. 61, 1854.

[12] William Thomson [Online]. Available: http://en.wikipedia.org/wiki/William_Thomson,_1st_ Baron_Kelvin

[13] James Clerk Maxwell [Online]. Available: http://www-history.mcs.st-and.ac.uk/Biographies/Maxwell.html

[14] J. C. Maxwell, On Physical Lines of Force, The London, Edinburgh and Dublin Philos. Mag. and J. Sci., March 1861.

[15] Oliver Heaviside [Online]. Available: http://en.wikipedia.org/wiki/Oliver_Heaviside

[16] B. Mahon, *The Man Who Changed Everything*: *The Life of James Maxwell. Hoboken*, NJ: Wiley, 2003.

[17] James Clerk Maxwell [Online]. Available: http://en.wikipedia.org/wiki/James_Clerk_Maxwell#Electromagnetism

[18] Heinrich Rudolf Hertz [Online]. Available: http://en.wikipedia.org/wiki/Heinrich_Hertz

[19] N. Tesla. (1900, Mar. 20). *System of transmission of electrical energy* [Online]. U.S. Patent 645, 576. Available: http://keelynet.com/tesla/00645576.pdf

[20] M. Cheney, *Tesla*, *Man Out of Time. Delta*, 1981.

[21] Nikola Tesla [Online]. Available: http://en.wikipedia.org/wiki/Nikola_Tesla

[22] G. Weightman, *Signor Marconi's Magic Box*. Da Capo Press, 2003.

[23] T. K. Sarkar, R. J. Mailloux, A. A. Oliner, M. Salazar-Palma, and D. L. Sengupta, *History of Communications*. New York: Wiley Interscience, 2006.

[24] Guglielmo Marconi [Online]. Available: http://en.wikipedia.org/wiki/Guglielmo_Marconi

[25] Hot Wire Barretter [Online]. Available: http://en.wikipedia.org/wiki/Hot_wire_barretter

[26] Reginald Fessenden [Online]. Available: http://en.wikipedia.org/wiki/Reginald_Fessenden

[27] L. De Forest. (1908, Feb. 18). *Space telegraphy* [Online]. U.S. Patent 8 79 532. Available: http://history-computer.com/Library/US879532.pdf)

[28] Audion [Online]. Available: http://en.wikipedia.org/wiki/Audion_tube

[29] Lee De Forest [Online]. Available: http://en.wikipedia.org/wiki/Lee_De_ Forest

[30] Lee De Forest [Online]. Available: http://www.leedeforest.org/hollywood.html

[31] A. Antoniou. On the roots of wireless communications [Online]. Available: http://www.ece.uvic.ca/~andreas/RLectures/RootsWCommuns-Web.pdf

Corrections

The author of [1] would like to report some corrections to his article as follows:

1) Page 15, column 2, line 4 should read "voice communications systems."
2) Page 15, column 2, line 10: replace "inventors" by innovators."
3) Page 16, column 1, line 4 should read "Bugs Bunny as that 'Wascally Wabbit'. Determined to cor-." (See [2].)

References

[1] A. Antoniou, "On the roots of wireless communications," *IEEE Circuits and Systems Mag.*, vol. 11, no. 1, pp. 15–25, 2011.

[2] In Wecognition of that Wascally Wabbit [Online]. Available: http://www.npr.org/templates/story/story.php?storyId=5588119

Digital Object Identifier 10.1109/MCAS.2011.941075

Date of publication: 27 May 2011