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HISTORY OF WIRELESS COMMUNICATION

In the earlier decades of the nineteenth century, magnetic and electric forces were believed to act instantaneously at a distance, a view prevalent in continental Europe and especially in Germany. But the obvious philosophical difficulties inherent in instantaneous action at a distance made this concept less acceptable to a few in the United Kingdom in general and to Michael Faraday in particular.

Faraday's Waves

In 1831 Faraday conducted a series of experiments on the magnetic effects of electric currents, during which he made his important discovery of electromagnetic induction, whereby an electric potential was induced in a conductor subjected to a changing magnetic field. In the course of these experiments, Faraday came to the conclusion that magnetic and electrostatic forces were not instantaneously effective at a distance but required a finite time for their transmission. We know now that electromagnetic energy is transmitted at the speed of light, but while continuing his experiments into 1832, Faraday had no means of detecting or measuring the very small time intervals necessary to confirm his theories. Furthermore he suggested, with remarkable intuition, that transmission of such forces took the form of some kind of wave motion. To establish his prior claim to the notion of wave motion, Faraday deposited a written statement in a sealed envelope with the Royal Society in 1832. The envelope was finally opened more than one hundred years later in 1937 by the then-president of the Royal Society, and found to contain, inter alia, the following words: "I am inclined to compare the diffusion of magnetic forces from a magnetic pole to the vibrations upon the surface of disturbed water, or those of air in the phenomenon of sound."

Faraday, the son of a blacksmith, was a brilliantly imaginative experimenter and theoretician but had only self-taught scientific education and no knowledge of mathematics. Because of this, his theories were regarded with some disdain by many contemporary scientists. However, there was one young mathematician, James Clerk Maxwell, who was most impressed by Faraday's concepts of magnetic fields and lines of force as set out in his paper "Experimental Researches in Electricity," read to the Royal Society in 1851.

Maxwell's Analysis

Maxwell already had an interest in this area, triggered while he was at Cambridge by the ideas of William Thomson, afterward to become Lord Kelvin; and Maxwell determined to submit Faraday's concepts to detailed mathematical analysis. As his studies continued he concentrated his attention on the possible nature of the medium through which electromagnetic forces could be propagated, wishing to devise a mechanical model exhibiting appropriate characteristics. This was a complex task, but by about 1862 he came up with a system of very minute rapidly spinning eddies or vortices, each surrounded by a layer of even more minute particles revolving in a direction opposite to that of the vortices themselves.

The vortices, with their outer layers of particles, could interact with one another in a manner analogous to a train of gear wheels, so that energy imparted to one vortex would be transferred to others and so progress through the medium.

Maxwell devised this mechanical model as one that could exhibit the sort of behavior necessary to embrace Faraday's concepts of lines of force and wavelike transmission of energy; but it was a convenient model only, and he was not so fanciful as to suggest that it represented anything much related to reality. Nevertheless it served his purpose of enabling rigorous mathematical analysis, culminating in his 1864 paper to the Royal Society, "A Dynamical Theory of the Electro-Magnetic Field." One of Maxwell's main hopes had been to derive the electromagnetic nature of light and heat, and this was triumphantly achieved in particular by one of the consequences of his theories, that electromagnetic wave propagation would travel at a velocity very close to the value for the speed of light that had been experimentally determined by others at the time.

The Maxwellians

Maxwell's analysis was deeply mathematical, making use of Hamiltonian quaternionic calculus and high-order differential equations, and at the time of his final publication in 1873, there were very few physicists with the intellectual ability to understand it. There were only three of note: Oliver Lodge and Oliver Heaviside in England, and the Irish professor George Francis FitzGerald of Trinity College, Dublin.

In 1873 Oliver Lodge, then a student at University College, London, attended a lecture by Maxwell at a meeting of the British Association and obtained a copy of his *Treatise* published in that year. Lodge did not study this closely until 1876, but when he did he quickly came to realize that Maxwell's equations implied not only the electromagnetic nature of light and heat, but also that there could be a whole spectrum of radiation with wavelengths both above and below those of visible light. Lodge was probably the first to appreciate that such electromagnetic waves could perhaps be generated electrically; and in 1879, after Maxwell's death, he began to give serious attention to this possibility.

FitzGerald too was studying Maxwell's theories at about this time and, in a paper to the Royal Dublin Society in 1882, suggested that electromagnetic radiation of about 10 wavelength could be generated by discharging a condenser (Leyden jar) through a circuit of very low resistance and low inductance. Furthermore, he clarified Maxwell's analysis to the extent of showing that the equations also led to the laws of reflection and refraction that had already been developed in the wave theories of light.

Another physicist who contributed significantly in this way was Oliver Heaviside, now best remembered for his 1902 theory of a reflecting ionized layer in the upper atmosphere, which, when physically verified some 20 years later, was named after him. Heaviside was a first-class mathematician and was already interested in Maxwell's papers. He reformulated much of the analyses in appreciably simpler terms, changing Maxwell's rather convoluted systems into notation of his (Heaviside's) own devising. He developed his own operational calculus and vector algebra and although contemporary mathematicians found it difficult to grasp at first, it is in this form that Maxwell's equations are familiar to students of today.

These three adherents and interpreters of the equations called themselves *Maxwellians.* They were scientists, and what was crucial to them was that the electromagnetic radiation implicit in the equations indicated that the unsatisfactory theories of instantaneous action at a distance could be discarded. While the theoretical analyses were their prime interest, they naturally hoped for experimental verification of the real existence of such radiation, and it was Lodge who pursued this most effectively.

Oliver Lodge

Oliver Lodge was born in Staffordshire, England, in 1851, the son of a pottery merchant. He received his scientific education at University College, London and while there attended a lecture by James Clerk Maxwell showing that oscillatory electrical discharges resulted in electromagnetic wave radiation propagating with the velocity of light. This fired Lodge with an abiding interest in what was eventually to become *wireless*.

Lodge quickly rose to be an eminent physicist, gaining his D.Sc. degree in 1877 and being appointed Professor of Experimental Physics at the University College of Liverpool in 1881. In 1887 he was elected Fellow of the Royal Society, the highest honor in British science, and he was knighted as Sir Oliver Lodge in 1902. He died at age 89 in 1940.

In 1887 Lodge undertook a series of investigations into lightning discharges and protection against them. He found by experiment that lightning flashes were oscillatory and followed this up with further experiments involving spark discharges from Leyden jars. In early 1888 he developed a famous experiment that he called the *recoil kick.* This involved generating oscillations by discharge of a Leyden jar capacitor into a long pair of wires and observing that a much greater spark would occur at the end of the wires when they were of a suitable length. He correctly surmised that this was due to a standing-wave pattern along the wires with a voltage antinode at the end. Furthermore, he understood that this condition would be satisfied when the wires were a half-wavelength long (or a multiple of this) and was thus able to determine experimentally the wavelength of the oscillations.

It can be seen therefore that he was conversant with the principles of resonance and tuning—or *syntony* as he called it—saying in 1888, "The natural period of oscillations in the wires will then agree with the oscillation period of the discharging circuit, and the two will vibrate in unison, like a string or a column of air resounding to a reed."

Although his experiments were largely confined to oscillations along wires, Lodge knew well that the electromagnetic waves were propagated in the space surrounding the wires rather than in the wires themselves. He knew also, being familiar with Clerk Maxwell's mathematical analysis, that the waves would be radiated into space and travel at the speed of light.

Thus we can see that Lodge had demonstrated experimentally the existence of electromagnetic waves as predicted by Maxwell's equations. But he had dealt only with waves guided along wires, since he had not then devised any means of detecting such radiation in free space.

In fact Lodge was not the first to observe electromagnetic waves along wires. In 1870 Wilhelm von Bezold observed such phenomena, detecting the waves by patterns formed by dust particles under the influence of electrostatic fields. However, he did not relate these observations to Maxwell's theories and his work attracted little notice.

Heinrich Hertz

At the same time that Lodge was undertaking his experiments, there were even more effective investigations being carried out by Heinrich Hertz in Germany. Hertz, the son of a lawyer, was born in February 1857. He turned eventually to science with a year's course at Munich, transferring in 1878 to the University of Berlin. Here he studied under Professor von Helmholtz, who gave much encouragement to one he recognized as an outstanding pupil. Finally, having been awarded his doctorate, Hertz was appointed assistant professor at the Physics Institute of Berlin in 1880.

Hertz had been brought up in the "instantaneous action at a distance" school of thought, but fairly early in his career he was introduced to Maxwell's theories by professor von Helmholtz, who encouraged him to attempt experimental proof of Maxwell's postulated *displacement current* in air or empty space. Hertz did not immediately take this up, but he was intrigued by the possibility that the concepts of displacement currents and electromagnetic waves could fundamentally change action at a distance theories.

A few years later he had been appointed professor at the Technical High School at Karlsruhe and found there in a collection of old physical apparatus a pair of Knockenhauer spirals, flat coils wound in wooden frames. Experimenting casually with these, he noticed that discharging a Leyden jar through one of the coils gave rise to a small spark across the open terminals of the other some distance away. This revived his earlier interests and he began to devote effort to theoretical clarification of Maxwell's equations. He became increasingly convinced that the equations could indeed give the true explanation of electric and magnetic field phenomena, and by 1884 he wrote "I think we may infer without error that if the choice rests only between the usual system of electromagnetics and Maxwell's, the latter is certainly to be preferred." But the physical existence of electromagnetic waves, and especially their finite velocity of propagation, needed to be established by practical demonstration, so Hertz undertook a series of experiments culminating in the famous ones of 1887–88 that proved the point beyond all doubt. It is true that others before him had, rather accidentally, observed electromagnetic radiation, notably Mahlon Loomis in the United States in 1872 and David Hughes in England in 1879, but neither of them understood what was happening or were familiar with Maxwell's work.

Hertz's investigations into the subject had involved generation, detection, and measurement of waves in free space, rather than along wires. Lodge generously acknowledged that Hertz's experiments were superior to his own and a more convincing proof of the validity of Clerk Maxwell's theories.

After his experiments Hertz undertook further theoretical interpretation and development of the Maxwell concepts, much helped by his correspondence with FitzGerald, Lodge, and Heaviside, which revealed significant earlier work by these Maxwellians that he had not previously heard of. Hertz's papers in 1890 were particularly important in the field of theoretical physics and were influential in setting the scene for the later achievements of Lorentz and Einstein. Hertz died in 1894 at the early age of 36.

Hertz was not primarily an experimentalist seeking to demonstrate the existence of electromagnetic waves. He was a theoretical physicist who conducted his famous experiments as a means of justifying his firm conclusion on a matter of fundamental scientific importance. The waves were not important to Hertz for their own sake: he saw them simply as affording proof that Maxwell's equations gave the true picture and that hitherto accepted theories of action at a distance must therefore be regarded as obsolete.

The three Maxwellians, Lodge, FitzGerald, and Heaviside, were of a like mind. They were satisfied with the fact that Hertz had experimentally demonstrated the real existence of electromagnetic radiation, and neither they nor Hertz himself concerned themselves with any possible practical applications such as communication.

Someone soon did, however: Richard Threlfall, as president of the Australasian Association for the Advancement of Science, proposed in 1890 using Hertzian waves for communication purposes. But no one else saw this as a practical proposition at the time, the range of a few yards achieved by Hertz in his Karlsruhe laboratory not seeming to offer very much.

Wireless Telegraphy Begins with Marconi

Five or six years went by with nothing very significant happening until Hertz's death in 1894. But ironically, this was one further event involving Hertz that had a most profound impact, for in that year the 20-year-old Guglielmo Marconi, on holiday in the Italian Alps, read an obituary describing the work of Hertz. He was immediately inspired to consider whether Hertzian waves might not form the basis of a wireless telegraph communication system, and dedicated himself to this idea for the rest of his life.

At the end of his holiday Marconi returned to the family home in the Villa Griffone near Bologna, and at once commenced experiments in his attic workshop where he had long since occupied himself with the electrical devices that had fascinated him from boyhood.

It is a well-known story how Marconi improved his apparatus and techniques to achieve greater and greater ranges during 1894–95; how he came to England in 1896 to make further progress; and how he spanned the Atlantic with the letter *S* in Morse in 1901. This story need not be told again here, but Marconi's relationship with Oliver Lodge is perhaps less well known and may usefully be described.

Lodge and Coherers

Although it was Hertz who first contrived to demonstrate the existence of electromagnetic waves in free space and that they exhibited reflection and refraction in the same way as light, it is true to say that Lodge knew and understood as much or more about the nature and behavior of the waves than anyone else in the latter years of the nineteenth century.

As already mentioned, Lodge was thoroughly conversant with resonance and tuning, and he also well understood the principles underlying radiation from antennas of various configurations. Although he knew that waves must be radiated into free space, he lacked any means of detecting them; and it was use of the crude, but just adequate, resonant spark-gap detector that enabled Hertz to effect his splendidly successful experiments.

But in 1889, the year after Hertz's demonstrations, Lodge made a discovery that was to prove a crucial step forward on the path to a practical wireless communication system. During his investigations into lightning and the analogous effects of spark discharges from Leyden jars, Lodge observed that two iron spheres or other metal surfaces very close together would at times fuse together to form a conducting path when subjected to a Hertzian wave pulse. He called this arrangement a *coherer,* saying that it formed "an astonishingly sensitive detector of Hertzian waves." Later, in 1893, he was made aware of the work of Edouard Branly in France, who had observed similar cohering effects with a glass tube filled with metal filings. Lodge immediately tried this for himself and found it very much more sensitive than his own iron spheres. In fact the phenomenon of coherence resulting from nearby spark discharges had been independently noticed by others some years earlier, including Guitard in 1850, Varley in 1866, and Onesti in 1874; but these predecessors had not in fact ascribed the effects to Hertzian waves, and neither had Branly in his 1890 experiments. In 1902 Lodge, in conjunction with Alexander Muirhead, invented a new form of coherer in which a knife-edged steel wheel grazed the surface of a small pool of mercury covered with a film of oil: an incoming radio pulse ruptured the thin oil film and allowed low-resistance contact between the steel and the mercury. This type of coherer was at least as sensitive as any other and a good deal more stable in operation.

Lodge did not at the time attempt to put his coherers to practical use, but Marconi used a filings version in his early apparatus. It was this, plus the use of elevated antennas and connection to earth, that enabled Marconi to develop and steadily improve his equipment to the point where it could be seen as a workable wireless communication system.

Lodge Versus Marconi

Marconi came to England in 1896 as a young man of nearly 22, with little theoretical knowledge of wireless principles but full of enthusiasm and dedication. He had a flair for publicity and in December gave a demonstration to members of the public, carrying a black box around the audience that rang a bell whenever a key at the end of the hall was depressed. Representatives of the press were present and the next day Marconi was headline news, hailed as the inventor of wireless. In fact Marconi was always quite modest and did not claim to be an inventor but rather that he "took up others people's ideas and inventions and improved them." But Lodge, and other scientists who had made significant contributions in the field, was naturally indignant about the adulation of a young Italian upstart: Lodge may thus be forgiven his testy comment in later years that "It was stale news to me and to a few others," but he then added more generously, "But whereas we had been satisfied that it *could* be done, Marconi went on enthusiastically and persistently till he made it a practical success."

Another area of interplay between Marconi and Lodge was tuning. As already mentioned, Lodge had a full understanding of the principles of resonance and tuning and in May 1897 he applied for a patent on his *syntony* ideas.

Tuning, and the resultant ability to separate one transmission from another, was of course a vital necessity for the development of Marconi's wireless system and he tried many different circuit arrangements with gradually increasing success. Finally in 1900 his famous "four sevens" patent was granted. It may appear strange that he was granted this patent when Lodge had registered his some years earlier; but it seems that it was not considered that one infringed the other, and it was ruled in court that the two were complementary rather than duplications. Nevertheless the existence of Lodge's patent was seen as an embarassment by the Marconi Company, especially when its validity was extended in 1911 by a further seven years. Accordingly, the Marconi Company negotiated with Lodge and bought his patent for a considerable sum.

The Lodge–Muirhead Syndicate

Another source of rivalry was the appearance of the Lodge–Muirhead Syndicate with a competing wireless telegraphy system. Although Lodge was basically uninterested in commercial exploitation of his Hertzian wave experiments and discoveries, such a venture was suggested to him by Dr. Alexander Muirhead after he had attended one of Lodge's lectures in 1894. This eventually resulted in formation of the Lodge–Muirhead Syndicate in which Lodge provided the scientific ideas and Muirhead—a very able telegraph engineer—the design of practical equipment.

By 1903 the Syndicate was ready with a well-designed and effective system incorporating the Lodge steel–mercury coherer, but they found themselves up against the Marconi Company's monopoly of coastal stations in the United Kingdom that it had negotiated with Lloyds of London from 1901, and the company's contracts with many shipping lines for exclusive use of Marconi equipment and operators.

Faced with this situation, the Syndicate could find only limited markets in the military field and in a few overseas countries. So despite its technical excellence, the Lodge–Muirhead system was not a commercial success and was wholly bought out by the Marconi Company in 1911, together with the Lodge tuning patent referred to previously.

Continuous Wave Telegraphy

Early radiotelegraphy was effected by spark trains produced as Morse signals by a telegraph key. The spark-induced oscillation bursts making up a dot or dash were randomly phased.

It was realized that continuous wave trains could be advantageous in offering narrower bandwidth transmission and hence the possibility of more precise tuning of transmitter and receiver, and various developments were undertaken to achieve this. The first was Marconi's synchronous spark discharger wherein multiple spark gaps on a rotating disk ensured that the oscillations from one gap would be so phased as to continue the oscillations from the preceding gap, giving a reasonable approximation of a continuous wave.

An alternative approach was the Poulsen system, based on earlier work by Duddell, using the negative resistance characteristic of an arc to generate continuous oscillation in a parallel resonant circuit. This was quite widely used by the German Telefunken company for a radio telephone system, but was not always successful due to the difficulty of maintaining a steady arc discharge.

Another alternative was the high frequency alternator. Difficulties here arose from the very high rotational speeds necessary to produce even quite modest radio frequencies; but Ernst Alexanderson of American General Electric designed very successful machines capable of 100 kHz at powers of hundreds of kilowatts. A later development in Germany was the Goldschmidt H.F. Alternator, which reduced the need for excessive rotational speed by an ingenious system of frequency multiplication within the machine. With suitable coils and pole pieces, and moderate speed, the rotor could produce a frequency of perhaps 15 kHz: This would be induced in the stator, setting up a rotating field therein. The stator field was arranged to rotate in the opposite direction to that of the rotor, so that an oscillation of double the frequency, 30 kHz was induced in the stator and $30 + 15 = 45$ kHz in the rotor. This 45 kHz was selected by a tuned filter resulting in a frequency of 60 kHz in the stator, the latter frequency being applied to the aerial for transmission. The Goldschmidt patents were bought up by the Marconi Company in 1913.

A difficulty with any of these machines was to maintain very precise alternator rotational speed, since even a small fluctuation would seriously detract from the potential for exact frequency stability and receiver selectivity. Particularly difficult was avoidance of speed changes with electrical load when the Morse key was operated; and this was compensated to some extent by a subsidiary key contact adjusting the alternator driving motor field when the key was depressed.

A final problem was that a continuous wave would by itself produce no sound in receiver headphones. To render Morse signals audible required the wave to be modulated at audio frequency. Crude modulation could be provided by a "ticker," a chattering contact that broke up the continuous wave into audio frequency groups. A better solution was to modulate the signals with a frequency about 1 kHz different from the main carrier to produce an audible "beat" note. This was achieved by Fessenden's heterodyne arrangement or by Goldschmidt's tonewheel.

Radio Telephony

Most early workers were content to communicate in Morse code telegraphy, but Reginald Fessenden, a Canadian working in the United States, considered radio telephony much preferable. In 1900 he achieved speech transmission over a distance of 1 mile using a spark transmitter with a spark repetition frequency of 10,000/s. But modulating speech on a spark signal has been memorably described as "like printing a newspaper on a roll of stair carpet," and articulation and background noise were very unsatisfactory.

Fessenden realized that a continuous wave carrier was necessary for satisfactory speech modulation, and he initially experimented with arc-based oscillators, but found an H.F. alternator more satisfactory. On Christmas Eve 1906, and again on New Year's Eve, he successfully transmitted speech and music from his Brant Rock station using an H.F. alternator. Remarkably, his experimental speech transmissions shortly before these two events were heard by chance at Fessenden's receiving station at Machrihanish in Scotland.

In the very early years of the twentieth century the only radio wave detector was the coherer; but this, being an on/off device, was suitable only for reception of Morse transmissions. Fessenden sought a continuously operating detector that would be suitable for demodulating speech signals on a continuous wave carrier, and in 1903 invented his Liquid Barretter, an electrolytic gas generator that did indeed respond continuously to the amplitude of a received carrier. This was used in conjunction with his 1906 speech and music transmissions, although by this time the Marconi Magnetic Detector was also in use and capable of amplitude demodulation, as were Fleming's diode of 1904 and the crystal detectors introduced by Braun, Austen, Pickard, Pierce, and Dunwoody from 1906.

Lee de Forest developed an arc-based radio telephone in 1907–8, which was supplied in some quantity to the U.S. Navy.

Vacuum Tubes

Based on Thomas Edison's discovery in 1883 of unilateral conduction of electric current between an incandescent filament and an adjacent "plate" electrode, John Ambrose Fleming in England devised his "oscillation valve" in 1904. In 1906 de Forest introduced a third "grid" electrode between filament and plate, thus inventing the triode tube: but he had little understanding of the operating principles of his invention, and it was the detailed studies of Howard Armstrong and Irving Langmuir that developed it into a reliable and practical device by 1915.

Also in 1915, Armstrong developed the regeneration principle and hence the triode oscillator, and this finally fulfilled the need for convenient and stable generation of continuous radio frequency oscillations that could readily be amplitude modulated for radio telephony applications. Furthermore, the triode could be configured as a sensitive detector of such signals.

Thus was opened the way to modern electronics and, a few years later, to entertainment broadcasting of speech and music.

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