

Chapter 1

The Great War and Wireless Communications

1.1 LAND-BOUND COMMUNICATIONS

1.1.1 The Battle of Tannenberg and the Electron Tube

The guns of August 1914 thundered along a western front from Belgium through northeastern France to the Jura mountains and along an eastern front from East Prussia through Russian Poland and Austro-Hungarian Galicia. (See Figure 1.1.) When war broke out at the beginning of that month, German leaders followed a strategy formulated by Alfred von Schlieffen nine years earlier in directing most of the available manpower and materiel against their enemies in the West, while fighting a holding action against the Russians. Fearful of a two-front war, they hoped to force France to sue for peace before the massive Russian armies could be brought effectively to bear on the much smaller German armies in East Prussia and Silesia.

In the West, the Germans moved steadily through Belgium, entering Liège on 7 August and Brussels on 20 August, and at the same time sharply repulsed the French offensive in Alsace-Lorraine. But news from the Eastern Front was, from the German point of view, quite disturbing. Russia's huge First and Second Armies, numbering some 200,000 men each, had mobilized and reached the front much faster than expected. On 17 August the Russians took the offensive, and on 20 August the Germans suffered a defeat at Gumbinnen. Soon a third of East Prussia was in Russian hands. There was widespread fear and some panic behind German lines, and refugees streamed westward toward Berlin.

This was the situation on 20 August when the chief of the German general staff, Helmuth von Moltke, placed a telephone call from his headquarters near the Western Front, in Koblenz, to General Max von Prittwitz, commander of the German Eighth Army in East Prussia. Prittwitz could talk only of the many difficulties of his

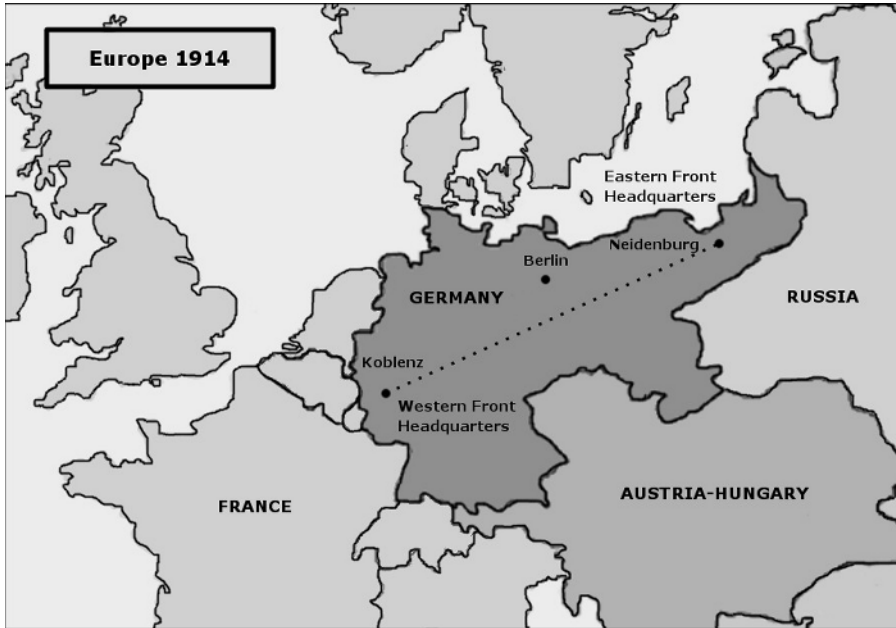


Figure 1.1. Map of Europe showing the disposition of military forces in August 1914 and the locations of Moltke's and Prittwitz's headquarters.

position, and his defeatism so appalled Moltke that on the following day he relieved Prittwitz of command. To take Prittwitz's place, Moltke called out of retirement the little-known, 66-year-old General Paul von Hindenburg and named Erich Ludendorff as Hindenburg's chief of staff. Thus—from one long-distance telephone conversation—began Hindenburg's rise to military and political prominence.¹ Battlefield success later led to his appointment as chief of the general staff and to the Hindenburg Cult of the later war years, when he served as the revered father figure behind whom Ludendorff operated as virtual dictator of Germany. And in 1925 came his presidency of the Weimar Republic that continued into the early 1930s, when he provided a respectable front behind which Adolf Hitler came to power.

Hindenburg and Ludendorff quickly assumed command of the Eighth Army. They moved almost all of their forces so as to entrap the Russian Second Army, trusting to the reliability of intercepted radio messages that the Russian First Army, positioned further north, would not advance.² There resulted, beginning on 26 August, the Battle of Tannenberg, which changed the course of the war. The Russian Second Army was devastated, the Germans taking more than 100,000 prisoners. Not only was Tannenberg one of the most complete victories in military history, it was

¹ Marshall, p. 60, and Falls.

² At this time the Germans regularly intercepted Russian radio messages. Barbara Tuchman writes [1962, p. 307]: "[Lieutenant Colonel Max] Hoffmann acknowledged the intercepts as the real victor of Tannenberg. 'We had an ally,' he said, 'the enemy. We knew all the enemy's plans.'"

also a decisive victory that put an end to the Russian threat to Prussian territory and allowed Germany to continue to give most of its attention to the Western Front.³

The telephone call that led to the change of command in the East Prussian army—and thence to the battle of Tannenberg and the rise of Hindenburg—was possible only because of a remarkable and very recent technological advance.

Since the introduction of the telephone in the late 1870s, engineers in many countries had sought ways to extend its range, particularly through the development of an effective telephone relay or repeater, a device able to restore the strength of an attenuated signal. Many inventors, beginning with Thomas Edison in 1877, proposed forms of microphonic amplification, with the mechanical oscillations of a telephone receiver actuating a microphone in a second circuit (whose stronger current made possible amplification).⁴ Even with the best of these devices, however, the amplification process so degraded the signal that they were scarcely practical. What finally allowed a successful telephone repeater was what is now known as the triode-electron tube. This device appeared at about the same time on the Continent and in the U.S.

A key event in the Continental line of development was a 1906 patent on a “cathode-ray relay” by Robert von Lieben of Vienna.⁵ A discovery made in 1903 by a German researcher, Arthur Wehnelt, had impressed von Lieben. Wehnelt was studying cathode rays (what we now think of as a flow of electrons), which could be produced in an evacuated tube when a high voltage was applied across two metal contacts inside the tube. Wehnelt discovered that if the negative contact (the cathode) was coated with calcium or barium oxide and heated to incandescence, a much lower voltage sufficed to produce cathode rays.⁶

The cathode rays bridged the gap between cathode and anode, completing a circuit. Lieben realized that one might obtain amplification if a way could be devised for a weak input current to control the stronger current from cathode to anode. His first successful device, patented in 1906, regulated the current by the effect on the cathode rays of a magnetic field produced by the input current. Working with Eugen Reisz and Siegmund Strauss, Lieben then made a much improved amplifier by replacing magnetic control with electrostatic control: a wire grid, connected to the input current, was placed between cathode and anode. In this arrangement, a negative charge on the grid diminished the cathode-ray current (because it repelled the

³ Falls, and Cruttwell, pp. 44–47.

⁴ Hunt, pp. 61–65. Two successful means of extending the range of telephony were the use of heavier lines and the placement, along the telephone lines, of inductance (either continuously or, more usually, at intervals with so-called loading coils).

⁵ Principal sources for the information on Lieben’s work are Siemens, pp. 11–14, and Tyne, pp. 73–83.

⁶ Wehnelt pointed out that if the heated electrode was made electrically positive and the other electrode negative, no current flowed, hence the device could be used to convert alternating current to direct current. Indeed, it was as a rectifier that Wehnelt patented the device on 15 January 1904.

If within the tube there is a very high vacuum, then almost all the current consists of a flow of electrons from cathode to anode. Whenever gas molecules are present in the tube, some of the current consists of motion of ionized molecules to the electrodes. In most early tubes, including Lieben’s and Lee de Forest’s (discussed below), ionized gas accounted for a large part of the current.

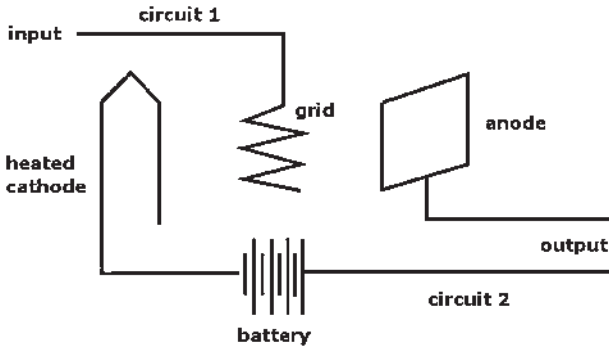


Figure 1.2. The weak input signal from circuit 1 controls the stronger current in circuit 2 because the flow of electrons from the cathode to the anode is highly dependent on the charge on the grid. Thus the signal in circuit 2 is an amplification of the signal in circuit 1.

electrons leaving the cathode) and a positive charge enhanced it. This device, patented in 1910, is now known as the triode, or three-element electron tube. A schematic triode is shown in Figure 1.2.

Four German companies were so interested in this tube that they jointly contracted with Lieben, Reisz, and Strauss for its further development.⁷ In 1912 there resulted an improved tube, known as the LRS relay, that was manufactured both by Siemens & Halske and by the Allgemeine Elektrizitäts Gesellschaft (AEG) and its subsidiary Telefunken. The LRS Relay was used in a number of telephone circuits shortly before the war and, in August 1914, in the circuit connecting the central army headquarters in Koblenz with the East Prussian headquarters, more than a thousand kilometers away. By the end of the war the Germans were using about a hundred telephone repeaters of the LRS type.

The U.S. line of development began with the invention in 1906 by Lee de Forest of a “three-electrode audion.”⁸ De Forest was influenced by the Englishman John Ambrose Fleming’s 1904 discovery of a two-electrode vacuum tube, which was used as a rectifier of alternating current and as a detector of high-frequency electromagnetic waves. De Forest’s key contribution was to add a control grid as a third electrode. Initially the audion was used only as a detector of wireless signals, but in 1912 several people recognized that the audion might be made to work as an amplifier. One of the first to succeed was Fritz Lowenstein, who applied in April 1912 for a patent on an improved form of the audion as an amplifier. Irving Langmuir at General Electric undertook a quantitative study of the audion’s behavior, and by the end of 1913 General Electric Company was manufacturing an amplifying tube under the name Pliotron. It was also in 1912 that de Forest himself succeeded in getting audio-frequency amplification from the audion, and he gained the interest of the

⁷ Tyne, pp. 234–240. The four companies were AEG, Siemens & Halske, Telefunken, and Felten & Guilleaume.

⁸ Principal sources for the information on de Forest’s audion are Aitken 1985, pp. 194–249, and Tyne, pp. 52–72, 84–92, 133–142.

American Telephone and Telegraph Company (AT&T) in the device. AT&T needed to make substantial improvements before the tube could be used as a telephone repeater, but this process was completed by 18 October 1913, when a triode repeater went into service on the line between New York and Washington, D.C. Such repeaters subsequently attracted great notice when they were used in the transcontinental telephone line between New York and San Francisco that opened on 15 January 1915.

The triode vacuum-tube is one of a small number of technical devices, such as the printing press and the internal-combustion engine, that have radically changed human culture. It defined a new realm of technology, that of electronics, which before the invention of the transistor, could be conveniently defined as the technology of devices incorporating electron tubes. Though invented in 1906, the triode was little developed before 1912, as its function—detecting wireless signals—could be performed satisfactorily by several other devices (such as the electrolytic detector or the crystal detector). But in 1912 there began a remarkable development of the technical potentials of the device. Before the end of the Great War it had found numerous applications and was being mass produced in huge quantities. This technical development and the proliferation of applications continued at a rapid pace in the decades after the war, to the degree that the world that emerged after the next Great War was, as a result of electronics, strikingly different in many respects from the world of 1914.

1.1.2 The Telegraph

Communication is of supreme importance in war, and war and the threat of war have often stimulated inspired efforts to improve communications. The chain of signal fires to warn of the approach of the Spanish Armada in 1588 and the semaphore system initiated by Claude Chappe in Revolutionary France are two examples.

Wartime communication serves two vital functions, permitting one to solicit and receive information and to direct military forces on land and sea. Improved communications allows more and better information to be used in decision making, and improved communications permits concerted action to be larger, more rapid, and more flexible. For example, the dispersion of an army along a front several hundred kilometers wide became practical only through the use of the telegraph.⁹ The immense size of armies in World War I, with chains of command having a dozen or so links, and the need to coordinate infantry, artillery, tanks, and aircraft made extreme demands on communications capabilities. Even on a single battlefield, communications were vital. (Wellington once remarked that the art of war was knowing what was happening on the other side of the hill.)¹⁰ Artillery, especially, depended upon rapid communication as its increased range frequently meant that gunners never saw the targets at which they were shooting.

⁹ Van Creveld, pp. 169–170.

¹⁰ Cusins.

The mainstays of diplomatic and military communications in the First World War were the telegraph and the telephone. Despite the increasing availability of triode telephone repeaters, the usual means of communications over more than a few hundred kilometers remained the telegraph. In particular, business between governments was conducted largely by telegraph.

Since wars often result from misunderstandings, one might suppose that telegraphy contributed to the long peace enjoyed by most European countries from 1815 to 1914. This was, indeed, the view expressed by a telegraphy expert in 1898, who wrote that the telegraph “has often been the means of averting diplomatic ruptures and consequent wars during the last few decades.”¹¹ Yet because telegraphic communications increased the speed of decision making, it may on occasion have contributed to the outbreak of war. This was the opinion of the French historian Charles Mazade, who wrote in 1875 that the Franco-Prussian war might have been avoided if diplomats had taken time for deliberation rather than reacting swiftly to telegraphed messages.¹² Telegraphy has been implicated too in the outbreak of the Great War: the historian Stephen Kern writes that diplomacy failed at that time because diplomats had not learned to cope with the volume and speed of electrical communications. A feverish tempo of questions and demands, constant use of the telephone, piles of telegrams, and ultimatums with time limits unthinkable in an earlier age contributed to Austro-Hungary’s declaration of war—delivered by telegram—on 28 July and the fateful decisions of the next few days.¹³

Military operations became heavily dependent on the telegraph. An indication of the volume of traffic is the estimate that the wired network built by the U.S. Army in Europe was conveying more than a million telegraph messages a month (more than 30,000 messages a day) by the end of the war.¹⁴ In response to the huge wartime need for communications, the German telegraph network increased its capacity through the use of a new high-speed telegraph, which was put into use as fast as the Siemens company could manufacture the devices.¹⁵ Naval operations, too, made much use of the telegraph. By 1890 almost all major ports worldwide had telegraphic service, prompting a U.S. Navy officer while on the China station to comment, “Now we have become mere messenger boys at the end of the cable.”¹⁶

The British government had long recognized the military significance of telegraphy. In the first decade of the century, it formulated policies for censoring telegraph service in the event of war, and by 1912 it had achieved its goal of invulnerability to such interruption on the part of other countries by having for “every important colony or naval base ... one cable ... which touches only on British territory or on the territory of some friendly neutral.”¹⁷ When war broke out, Britain moved rapidly to isolate its main adversary; the first British act of war was the severing of five German under-

¹¹ Charles Bright quoted in Headrick, p. 75.

¹² Headrick, p. 74.

¹³ Kern, pp. 275–277.

¹⁴ *Report of the Chief Signal Officer*, p. 186.

¹⁵ Siemens, p. 8.

¹⁶ Howeth, pp. 10–11.

sea cables, leaving Germany only one transoceanic link, the Liberia-Brazil cable—it too was cut by 1915—and the first British military engagement was a raid on the German cable station at Lome, Togo.¹⁸ The severing of these cables meant, for one thing, that German cruisers away from the Continent were almost incommunicado, as they were reluctant to risk giving away their position by using wireless.¹⁹

The Germans, too, sought to disrupt enemy communications. They made attacks on three British cable stations overseas, and they severed land lines connecting Britain to India and the Baltic cables connecting Britain and France to Russia.²⁰ The disruption—and threatened disruption—of telegraph links gave a great impetus to the development of wireless communication. Telegraphy suffered from two other shortcomings: a telegraph link required trained operators on both ends, and the encoding and decoding of a message took some time. Hence, on the battlefield it was principally the telephone that gave commanders up-to-the-minute information and control-by-wire.

1.1.3 The Telephone and the Battle of Neuve Chapelle

Telephone lines connected each unit to its subordinate and superordinate units, so that, for the first time in a major war, commanders at different levels (such as company, brigade, division, and corps) could be in direct contact. This allowed the exchange of information and tactical ideas and the immediate conveyance of orders (Figure 1.3).

The military telephone system appears in Arnold Zweig's novel about the war on the Eastern Front, *The Case of Sergeant Grischa*. Zweig described it as “that great net, that tissue of slender telephone wires which, like a spider's web, brought that vast land within the hearing of its masters”.²¹ He wrote of the signalers, the telephone stations, the labor companies, and the repair parties needed to construct, operate, and maintain the system:

*... there stretched over the land a network of black lines in all directions: wires, flexible and coated with rubber, soaked in protective solution, and covered with twisted thread. Like thin black nerves, they coiled over the earth in shallow ditches, just beneath the surface, or traversed the air on tall poles. They accompanied the telegraph wires along all the railway lines; they crossed the forests on straight paths decreed for them. The telephone wires of the army hung high above the earth in the forest tree-tops; their course was marked on the map and the line was carefully secured whenever necessary. In the summer no one paid any attention to them, but in the winter they paid dearly for this neglect. The forests, where the wind-spirit waved his snowy hands, took little heed of these black rubber-coated wires.*²²

¹⁷ Headrick, pp. 98–99. The quotation is from a British government report of 26 March 1902.

¹⁸ Beesly, p. 2.

¹⁹ Cruttwell, p. 74.

²⁰ Headrick, pp. 141–142.

²¹ Zweig, p. 71.

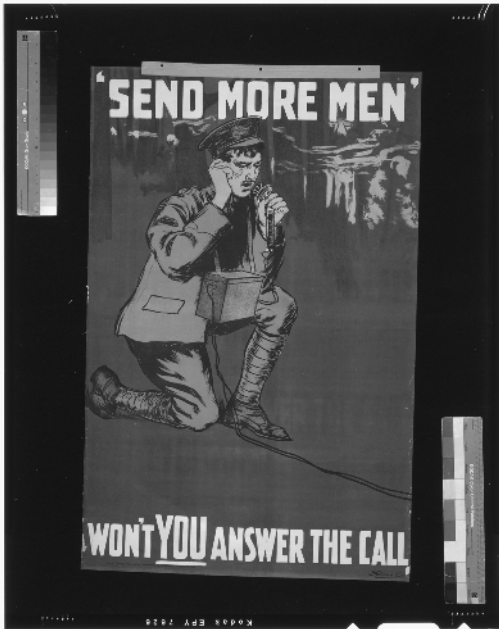


Figure 1.3. Field telephone in World War I (photo courtesy of the Library of Congress, World War I Posters, LC-USZC4-12670).

At the front, the telephone lines connecting artillery observers to those directing the guns were extremely important. (The telephone could even be used in observation balloons, as the telephone line could be attached to the tethering cable.)²³ The telephone was used, too, to warn of the firing of a long-range gun—a shell could be as much as five minutes in flight—in those cases where a telephone line joined an observing post near the enemy gun with the intended target.²⁴ And telephone lines were unrolled to keep advancing units in touch with base camps. The battlefield importance of telephony is suggested by the efforts of the U.S. Signal Corps to provide communications for the American Expeditionary Force in the final year of the war: the Signal Corps strung approximately a quarter million kilometers of telephone wire and set up 273 telephone exchanges, and by the time of the armistice, Signal Corps telephone traffic had reached some 150,000 local calls and 4000 long-distance calls every day. Advanced techniques, such as multiplexing, were exploited; 4 copper wires could be made to simultaneously carry 3 telephone circuits and 12 telegraph streams (6 in each direction).²⁵

²² Zweig, p. 298.

²³ Clark.

²⁴ Cruttwell, p. 531.

²⁵ Kennelly, pp. 225–228, and *Report of the Chief Signal Officer*, p. 174. For U.S. use some 100,000 field telephones were manufactured; the telephone was a modification of one Western Electric had made before the war for the forestry service [*Report of the Chief Signal Officer*, pp. 10, 232].

Though the telephone was clearly the favored means of communication in the field, it was also, as experience repeatedly showed, a deficient means. One problem was that telephone lines were frequently tapped by the enemy.²⁶ Much more serious was a problem revealed clearly in the battle of Neuve Chapelle.

In August and early September 1914, the Germans moved rapidly through Belgium and deep into France, threatening to take Paris. An Allied counterattack, the “Miracle of the Marne”, pushed the leading German forces back to the Aisne River, and there followed a series of flanking movements that extended the battle line northwestward to the sea. The line thus established, stabilized by entrenched troops with machine guns behind barbed-wire barriers, would hardly move in the next three and a half years of intense combat. Commanders then, of course, did not know this and continued to believe the war could end quickly with one breakthrough. In fact, despite dozens of major attempts in four subsequent years of fighting on the Western Front, the opposing line was cleanly broken only three times.²⁷ The first of these penetrations was the battle of Neuve Chapelle.

In February 1915 Russia suffered another colossal defeat when the Germans destroyed its Tenth Army, taking 110,000 prisoners, at the second battle of the Masurian Lakes. Germany decided to reverse the von Schlieffen strategy and was now sending as many troops as it dared to the Eastern Front, trying to knock Russia out of the war and standing on the defensive in the West. France and Britain, therefore, felt obliged to relieve the pressure on their ally by launching a major offensive. Sir John French, commanding the British forces, decided to break the enemy line at Neuve Chapelle, not far from the German held railway junction at Lille, with an assault launched early in the day on 10 March.

It began with a 35-minute “hurricane bombardment” that was one of the first demonstrations of the unprecedentedly intense use of artillery that became characteristic of the war. This opening barrage carried more shells than had been fired in the whole of the Boer War, fought from 1899 to 1902.²⁸ The Germans likewise made heavy use of artillery. One unforeseen result was an almost complete disruption of telephone communications, even though signalmen worked constantly to mend line breaks and repeatedly laid new line. So although British units broke through the German line, the lack of communication—laterally at the front, between advancing units and commanders trying to coordinate actions, and between guns and observers—precluded exploitation of the initial successes. According to one historian, “it was glaringly obvious that the breakdown in communications, the inevitable lack of speedy reaction to the situation at the front, the shattering of the telephone lines between observers and the guns, had been almost wholly responsible for the frustrations and delays.”²⁹ The Germans succeeded in reforming their trench line just a thousand yards or so farther back, and the battle

²⁶ Hartcup, p. 78.

²⁷ Marshall, p. 87.

²⁸ Gilbert, p. 132.

²⁹ Macdonald, p. 140.

ended, in the words of another historian, “Neither a defeat nor a victory, but a two-sided blood sacrifice. . . .”³⁰

The battle of Neuve Chapelle, intended to be a decisive blow, instead showed how difficult it would be to break the stalemate. The vulnerability of telephone lines to artillery fire continued throughout the war. Even along stationary lines, enormous numbers of shells were fired, and an assault could be preceded by a barrage of a million rounds. On one occasion on the Western Front, an artillery barrage caused 350 breaks in a 1-kilometer line.³¹ A contemporary assessment was that, in the forward zones of warfare, “the intense effect of modern artillery fire has practically ruled out the use of wired communications.”³² Late in the war, the practice of preceding an assault by a massive bombardment fell into disfavor, as it removed the element of surprise, yet Ludendorff and other commanders still advocated the use of a short artillery barrage before an attack, specifically to disrupt enemy communications. Some immunity from shellfire could be obtained by burying the line 6 feet underground, and the British began doing so in 1915.³³ Still, telephony was hardly suited to offensive operations. Indeed, the historian Peter Dewey has written: “Perhaps the greatest weakness of the attack lay in the lack of communication once it had begun. Commanders in the trenches were almost powerless to communicate with their advancing troops.”³⁴

1.1.4 Ground Telegraphy

To overcome such problems—which of course also beset traditional telegraphy—there was frequent reliance on the ancient means of battlefield communication, couriers (dispatch riders and, much more usually, runners), and, occasionally, on carrier pigeons, messenger dogs, and signal flags. (Adolf Hitler was one of the thousands of soldiers who served as dispatch runners.) An electrical technology, signal lamps, came to be quite important, as lamps suitable for daytime as well as nighttime use were developed, including ones using ultraviolet light in order to be invisible to the enemy.³⁵ Another electrical technology that avoided reliance on electrical lines was TPS (*télégraphie par le sol*), also called “ground telegraphy” and “earth current signaling.”³⁶ The experiences at the battle of Neuve Chapelle and other early actions gave great impetus, in mid 1915, to the development of this technique.

Engineers had long known that electric impulses could be detected after traveling several hundred meters through the ground. The enterprising engineer Gustave-

³⁰ Marshall, p. 87.

³¹ Kennelly, p. 230.

³² Cusins, p. 768.

³³ Woods, pp. 126, 195.

³⁴ Dewey.

³⁵ Kevles, p. 137.

³⁶ Sources for the information on TPS are Amoudry, pp. 179–181; Blake, pp. 332–334; Hartcup, pp. 76–78; and Kennelly, pp. 243–244.

Auguste Ferrié, who headed the French Radiotélégraphie Militaire, had two important insights: the newly available electron tube could significantly extend the range of this technique, and it might then be of enormous value in the fighting on the Western Front. He made improvements in the signal generator and in the receiver—notably by the use of a triode amplifier—and achieved a usual range of several kilometers. The transmitter was essentially a buzzer (an electromechanical device that interrupts the circuit at a very high rate) powered by a battery. Ferrié found that there was less interference when high tones were used. The receiver was an amplifier, employing a triode electron tube. Earth connections were usually made by driving steel pins into the ground; often a short length of insulated wire was laid along the ground and anchored at each end by a spike.

These devices began to be used in large numbers in 1916, and by the end of the war the French had produced almost 10,000 of them for use by the Allies. The Germans also deployed a system of ground telegraphy; it was mainly the work of a young mathematician, Richard Courant, who became famous after the war for his work on quantum mechanics.³⁷ So did the Americans.³⁸

Users of ground telegraphy discovered that their receivers frequently could pick up telegraph and telephone signals from lines buried nearby. They were thus used to tap enemy lines and also to receive one's own telegraph or telephone signals when a line had been severed. These receivers came to play a large role in eavesdropping, a subject considered more fully below.

Its portability and its freedom from electrical lines made ground telegraphy an important means of communication during the Great War. It was a technique, however, that scarcely outlived the war. Even before war's end it began to be displaced by another wireless communication technique, one with a much wider applicability and a much greater potential.

1.2 COMMUNICATION THROUGH THE ETHER

1.2.1 Origins of Wireless Telegraphy

The leaders in developing the new communications medium were the navies of several nations. They had long used other wireless means, such as lanterns and gunfire, to signal from ship-to-ship or ship-to-shore. The availability of telescopes led in the mid seventeenth century to signal-flag systems, which underwent considerable refinement over the next two-and-a-half centuries.³⁹ A major advance came with electric-light signaling, which the U.S. Navy adopted in 1878 for conveying Morse

³⁷ The famous physicist Arnold Sommerfeld also contributed to the German development of ground telegraphy [Hartcup, p. 77]. In the United States Lee de Forest patented a system of signalling by earth currents [Blake, p. 334].

³⁸ A 2-way earth telegraphy set, the SCR-76, was designed by Western Electric engineers [*Report of the Chief Signal Officer*, p. 290].

³⁹ Howeth, pp. 4–10.

code.⁴⁰ All of these signaling methods were slow and had a range of only 10 or 20 kilometers, even under the best of weather conditions. Hence when wireless communication by electromagnetic waves became possible, many naval officers showed interest.

The origin of radio may be traced back to James Clerk Maxwell's prediction, made in the early 1860s, of the existence of electromagnetic waves (thus called because they consist of interacting electric and magnetic fields) or to Heinrich Hertz's demonstration of their existence a quarter century later. In 1892 William Crookes attracted international notice in arguing that these waves provided an excellent means of communication, yet the exploitation of this possibility, either for commercial or military purposes, took several years.⁴¹ The person most responsible for turning the laboratory demonstration into a useful device was the young and largely self-taught Guglielmo Marconi.

In the late 1890s Marconi developed a wireless system that drew heavily on the achievements of contemporaries, notably the Hertzian transmitter of his teacher Augusto Righi and the coherer detector of Édouard Branly (which registered the presence of an electromagnetic wave by the changed conductivity of a tube of metal filings). (See Figure 1.4.) The historian Hugh Aitken writes of Marconi: "The original acts of creative insight were seldom his. Where he excelled was in the indispensable process of critical revision."⁴² Marconi succeeded not only as what would today be called a systems engineer, but also as an entrepreneur.

After extensive experimentation with antenna designs (which showed him that he could achieve much greater distances with a grounded vertical antenna), Marconi in 1896 put together a system capable of signaling several kilometers and soon obtained an English patent. The following year a company was formed to exploit the patent, and in 1900 a second company, specifically for marine communications, was established. What came to distinguish the Marconi companies was their provision of a complete service, not only the equipment but also the personnel to operate and maintain it.

Effective use of radio was hindered by a problem associated with early transmitters. Most pre-war transmitters were the so-called spark oscillators, which generated radio-frequency waves in extremely short pulses that were rapidly damped. Both the short pulse-length and the damping caused a substantial broadening of the signal spectrum (that is to say, the signal contained a wide range of frequencies). (See Figure 1.5.) Interference between two simultaneous transmissions was then almost inevitable, since they could not be sharply tuned to different frequencies. It was widely recognized that a reliable generator of waves of a single frequency could

⁴⁰ Howeth, p. 10.

⁴¹ The belief that Oliver Lodge's Hertzian-wave demonstration in 1894 (at the annual meeting of the British Association for the Advancement of Science) included the transmission and reception of Morse code, as Hugh Aitken concluded [Aitken 1976, p. 123], has been convincingly refuted in Sungook Hong's 1994 article in *Technology & Culture*.

⁴² Aitken 1976, p. 187. The main source for this paragraph is Aitken 1976, pp. 179–297.

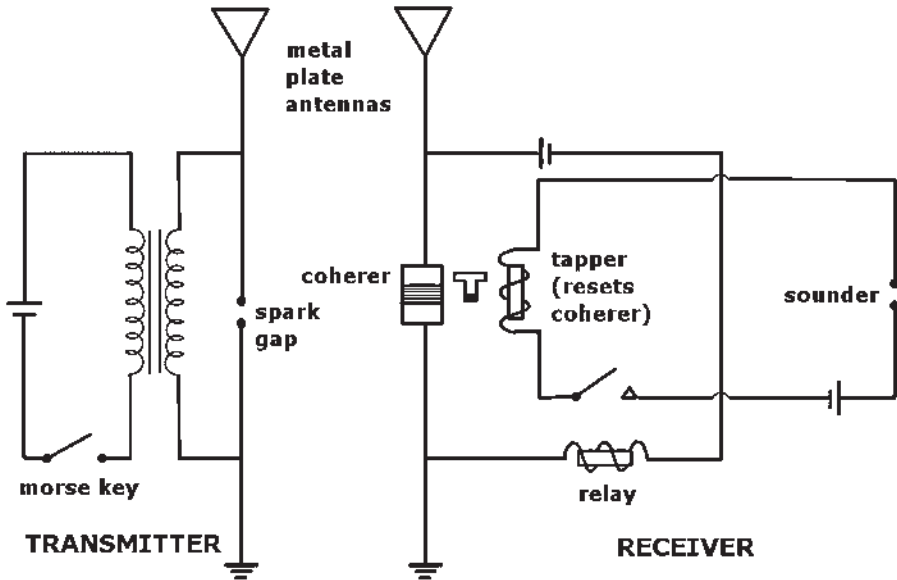


Figure 1.4. The system of wireless communication that Marconi developed by the turn of the century.

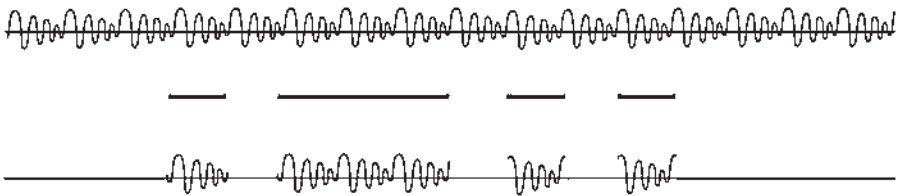


Figure 1.5. These curves indicate how Morse code is carried by the output of a spark transmitter: at the top is output typical of a spark transmitter, in the middle is the code for the letter L (dot-dash-dot-dot), and at the bottom is the transmitted signal.

solve this problem. (As we will see, another crucial advantage of a continuous-wave generator was that it made possible transmission of voice signals.) Efforts to produce a continuous-wave transmitter predated the war, and two means of generating continuous waves were already successfully developed: the Poulsen arc transmitter and high-frequency alternators.

At the beginning of the nineteenth century, Humphry Davy had observed that, under certain conditions, if he made a small break in an electric circuit the current continued to flow in a steady arc-discharge across the gap, and he exploited the phenomenon to produce an extremely bright light (later commercialized as arc lighting). Almost a century later, the Danish engineer Valdemar Poulsen, building on the recent work of the English scientist William Duddell, showed how to obtain regular oscillations in the radio-frequency range from a steady arc-discharge, and in 1903

he demonstrated transmission over 150 miles.⁴³ In 1913 the U.S. Navy began building Poulsen-arc transmitters,⁴⁴ and most of the major units of the British navy were equipped with Poulsen transmitters by the end of 1916.⁴⁵ Though the arc transmitter easily outperformed spark transmitters, its range was less than hoped for, as it proved difficult to increase the power much beyond 30 kilowatts.⁴⁶

Greater power was obtained with radio-frequency alternators. Generators of alternating current for electric power provided, of course, great power—a capacity of several thousand kilowatts was common in the first decade of the century⁴⁷—but at a frequency, typically 50 or 60 Hertz (cycles per second), far below what was needed for radio. The person most responsible for the successful redesign of alternators to produce radio frequencies was Ernst F.W. Alexanderson of General Electric, and in 1909 that company began producing the first 100-kilohertz, 10-kilowatt alternator.⁴⁸ In February 1917, General Electric delivered a 50-kilowatt alternator to the Marconi wireless station in New Brunswick, New Jersey; the station was taken over by the navy after the United States entered the war in April 1917, and beginning in February 1918 it was regularly used for official radio traffic to Europe.⁴⁹ This transmitter was used when direct radio communication with Germany (through the station at Nauen, near Berlin) was established in October 1918.⁵⁰ A still more powerful radio-frequency alternator was built by the French company Société française radioélectrique (SFR); its 125 kilowatts of power were ample for communication across the Atlantic.⁵¹

By war's end, it was clear that the future of radio transmission lay with continuous-wave generators. Some engineers thought the Poulsen arc would become the dominant type, others the high-frequency alternator. In fact, as we will see, the future lay with a third means of generating continuous waves.

1.2.2 Wireless at Sea

In the first decade of the century, the Marconi companies and other promoters established a place for wireless in maritime and naval operations. In 1900 the Cunard and White Star lines began installing wireless apparatus on their liners, and in 1901 Lloyds of London, the marine insurance firm (which had more than 1000 agents in ports around the world), signed a contract with the Marconi Company. In the U.S. the Radio Ship Act of 1910 required all ocean-going vessels carrying 50 passengers

⁴³ Howeth, p. 133.

⁴⁴ Aitken 1985, pp. 93–95.

⁴⁵ Hartcup, p. 128.

⁴⁶ Aitken 1985, pp. 96–97.

⁴⁷ Hunter and Bryant, p. 346.

⁴⁸ Brittain 1992, p. 67.

⁴⁹ Brittain, pp. 117–131.

⁵⁰ Brittain, p. 130.

⁵¹ Amoudry, p. 177.

or more to be fitted with radio equipment. Besides for ship-to-shore and ship-to-ship communications, radio was important in another way; accurate navigation at sea required accurate timekeeping, and just after the turn of the century the Greenwich Observatory began broadcasting time signals.

Navies, too, found wireless a boon to operations. The British navy began equipping its ships with Marconi wireless sets in 1900, and in 1903 the newly created Telefunken began receiving orders from the German navy.⁵² As early as 1905 wireless played a major role in combat, allowing the Japanese navy to surprise the Russian navy at the time of the battle of Tsushima.⁵³ The U.S. Navy, however, was unusually slow to adopt the new technology; it was not until 1913 that tactical signaling by wireless became regular practice.⁵⁴

At the highest level, radio changed the way navies fought. According to the British historian C.R.M.F. Cruttwell, "... the Admiralty from its great wireless masts in Whitehall necessarily directed and controlled strategy far more powerfully than in earlier wars."⁵⁵ Wireless finally ended the need for dispatch vessels, which carried messages to and from ships at sea. It also made possible the new British strategy of distant blockade. The traditional British practice of cutting off enemy trade by close blockade of harbors was too dangerous because of torpedo boats and U-boats, but good communications and reconnaissance allowed the safer alternative to be almost as effective.⁵⁶

Wireless was also important at the tactical level. In fleet operations, however, the British, concerned that wireless transmitting would reveal their locations and aware of the danger that their codes might be broken, maintained wireless silence when using other forms of signaling made this possible.⁵⁷ German warships made greater use of wireless, not knowing how skilled the British were at locating transmitters and falsely believing as we will see below, that their codes were secure.

Wireless communication was especially important for submarines, as their deployment could often benefit from recently received information about threats from the enemy and about possible targets. In April 1915 Admiral John (Jacky) Fisher reported to Winston Churchill, First Lord of the Admiralty, that German U-boats were transmitting and receiving signals, day or night, at distances up to 300 miles and termed it "vitally necessary" that the British submarines be capable of the same.⁵⁸ (British submarines on patrol could not report sightings in a timely way

⁵² Headrick, pp. 118, 123.

⁵³ Griset, p. 104, and Okamura, p. 54.

⁵⁴ Susan Douglas 1985.

⁵⁵ Cruttwell, p. 62.

⁵⁶ Schmitt, p. 40.

⁵⁷ Beesly, p. 32. Communicating by signal flag was neither rapid nor reliable. For example, at the Battle of Dogger Bank early in the war orders conveyed by signal flag were misinterpreted; otherwise the British would have achieved a much greater victory [Beesly, p. 62].

⁵⁸ Hartcup, p. 128.

because, in the first year and a half of the war, their wireless sets had a range of only 30 miles or so.)⁵⁹

To achieve longer-range communications, two avenues were pursued. The first was the development of more sensitive receivers. Electron tubes helped here in three ways: as detectors (the purpose for which both Fleming's diode and de Forest's triode were invented); as amplifiers (the purpose of electron tubes in telephone repeaters); and as local oscillators for what is known as "heterodyning".

The process of heterodyning—whereby the incoming signal is combined with a continuous wave generated in the receiver—had been proposed before the war as a way to gain sensitivity.⁶⁰ (The so-called beat frequency—equal to the difference between the input frequency and the local-oscillator frequency—carries unchanged the audio signal.) There were, however, no good sources of local oscillation at appropriate frequencies, as neither the alternator nor the Poulsen arc could be readily scaled down to the right size.⁶¹ The electron tube proved to be ideal as a small, low-power oscillator, and, indeed, it was for heterodyning that the electron tube first became standard in naval apparatus.⁶²

The second avenue toward long-range radio was the development of more powerful and effective transmitters. During the war the most powerful and effective type was the Poulsen-arc transmitter. Built in various sizes—the largest for the highest-power land stations, the smallest for transmitters for submarines—the arc transmitter functioned well, both for telegraphy (its usual use) and telephony. For the latter application there gradually emerged a rival in the electron-tube oscillator. Alexander Meissner, Telefunken's chief engineer, produced an effective transmitting tube early in 1915,⁶³ and engineers in Britain and the United States achieved similar results at about the same time. As we will see below, tube transmitters were developed for the mobile use of radio telephony, and for a short time this seemed the only area where it was preferable to the Poulsen arc.

1.2.3 Wireless on Land and in the Air

With the availability of powerful transmitters, radio became a vital means of long distance communication for several governments. Its oceanic cables severed, Germany could communicate with its colonies and ships away from the Continent only by radio; the transmitter at Nauen could reach America, South-West Africa, and China.⁶⁴ France relied on radio to communicate with its allies in Eastern Europe

⁵⁹ Hezlet, p. 97.

⁶⁰ Heterodyning was first introduced, by Reginald Fessenden in about 1901, as a way of making audible the Morse-code signals sent by a continuous-wave transmitter [Aitken 1985, pp. 58–59].

⁶¹ Gossling. Small Poulsen-arc oscillators were, in fact, developed for use in heterodyning, but were soon displaced by vacuum-tube oscillators.

⁶² Gossling.

⁶³ Hartcup, p. 127.

⁶⁴ Beesly, p. 30.

(Russia, Rumania, Greece, Montenegro, and Serbia) and with certain of its colonies.⁶⁵ After U.S. entry into the war, a radio link between Lyon and Sayville, New York permitted the exchange of 40,000 words per week between the two allies.⁶⁶ The most important of the French transmitting stations was at the Eiffel Tower, which Alexandre-Gustave Eiffel had made available in 1903 to the French military for radio communication.⁶⁷ It was, indeed, from the Eiffel Tower that the message stopping the war was transmitted at 5:00 am on 11 November 1918.⁶⁸

Armies in the field made considerable use of wireless. Because early sets were not very portable, wireless was used principally between headquarters, though small radios for use in the trenches were developed before the end of the war.⁶⁹ In the first year of the war, Moltke made wireless a favored means of communicating with general headquarters, but his lack of radio capacity, a problem greatly exacerbated by intentional interference from the Eiffel Tower station, caused severe communication deficiencies.⁷⁰ Electron-tube transmitters, which became available for field use toward the end of the war, alleviated two difficulties associated with earlier transmitters: the much narrower signal spectrum made it easier to tune out other transmissions; and the smaller size improved portability.⁷¹ These transmitters were particularly welcome for communicating between gunners and forward observation posts.⁷²

These, as well as the naval uses of wireless mentioned above, were applications of wireless telegraphy, which conveyed Morse code or some other discrete code. As early as 1900 Reginald Fessenden, a Canadian-born electrical engineer, had recognized that radio waves could transmit voice and music, provided one found a source of continuous waves at radio frequency. The audio signal could be imposed on the continuous wave at the transmitter and extracted from the incoming signal at the receiver. (See Figure 1.6.) Fessenden's idea was that one could design an alternator able to produce radio-frequency oscillations (in the neighborhood of 100,000Hz, rather than the 60Hz produced by many electric-power generators). General Electric pursued this idea and, as mentioned above, built a series of radio-frequency alternators. In 1906 at Brant Rock, Massachusetts, Fessenden used one of them for experimental broadcasts of speech and music that were received by wireless operators on nearby ships.⁷³

⁶⁵ Griset, p. 105, and Amoudry, p. 185.

⁶⁶ Griset, pp. 105–106.

⁶⁷ Libois, pp. 52–53. The Eiffel Tower, completed in 1889, was the tallest structure in the world for four decades.

⁶⁸ Amoudry, p. 201. The message transmitted read “Marshall Foch to the Allied commanders: Hostilities will cease at 11:00 a.m.”

⁶⁹ Kennelly, p. 234.

⁷⁰ Cruttwell, p. 25, and Amoudry, p. 155.

⁷¹ Eoyang, p. 29. Early in the war the problem of mutual interference was so severe that the British army allowed only one radio set per division along the front.

⁷² Cusins.

⁷³ McNicol, pp. 74–77.

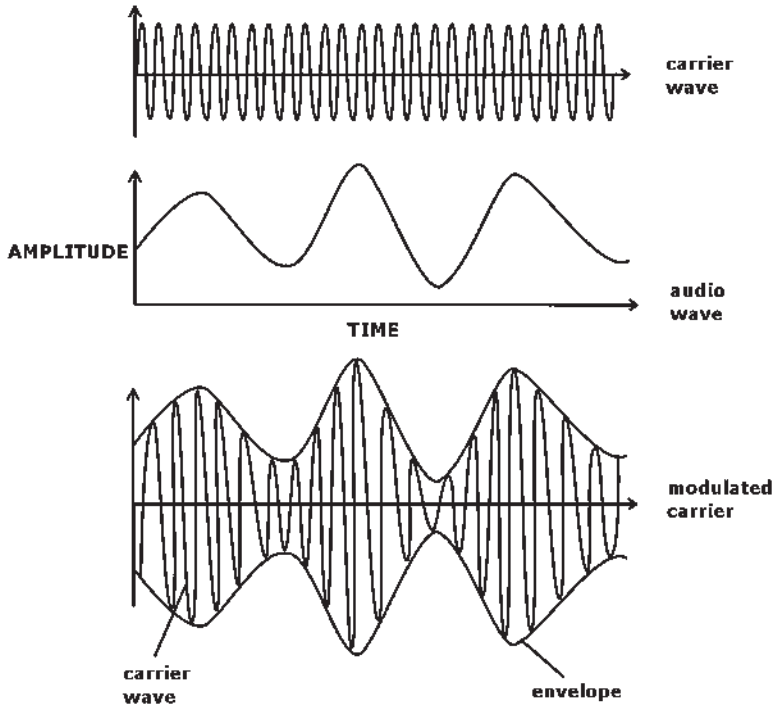


Figure 1.6. These curves indicate how a voice signal is carried by a continuous wave, which is then called the carrier wave: at the top is a single-frequency wave, in the middle is an audio wave produced in speaking, and at the bottom is the carrier wave modulated by the audio signal.

The two other sources of continuous waves—the Poulsen arc and the electron tube—were also applied to radio telephony. In 1914 Bell engineers began to investigate electron-tube circuits as oscillators, and in April 1915 they transmitted speech from Montauk, Long Island to Wilmington, Delaware. These engineers then constructed a transmitter containing some 300 oscillating tubes (in order to reach a power of two to three kilowatts) and in October 1915 successfully transmitted speech across the Atlantic (to the Eiffel Tower station of the French military).⁷⁴ During the war and in the first few postwar years, the Poulsen arc, along with the radio alternators, were favored over the electron tube because they generated much more power. Both, however, were much larger, so not suited to portable radio telephones.

Radio was also important to the military use of aircraft. Aviation underwent rapid development during the war, both in numbers—by Armistice Day some 200,000 aircraft had seen service—and in capabilities. Speed increased from 100 to 200 km/hr, motor power from 100 to 300 horsepower, flying height from 1200 to 9000 meters, and flight duration from 5 to 9 hours.⁷⁵ The most important military function was reconnaissance.⁷⁶ Here rapid communication was essential, especially

⁷⁴ Fagen, pp. 364–368.

⁷⁵ Braun, p. 202.

when the purpose was the directing of artillery fire. In 1912 the U.S. Navy successfully tested a radio transmitter and receiver mounted in an aircraft, but the considerable weight of the apparatus and the difficulty of communicating in telegraphic code made wireless unpopular with aviators.⁷⁷ In Germany airplane transmitters underwent testing as early as 1912. By the end of 1916 they were standard equipment, and German planes began to be equipped with receivers as well.⁷⁸

One of the most important improvements was making radio apparatus smaller and lighter. Using an on-board generator (run by the airplane motor or a wind-driven vane) rather than batteries reduced the weight further. Since keying in Morse code was difficult in that era's airplane and also required considerable training, alternative means were sought. The Germans experimented with automatic code senders (so the aviator needed only to key in letters) and with wireless transmission of drawings from aircraft to the ground.⁷⁹ Cylinder phonographs were used to record observations in the air, though with this device the information could not be shared until the flight ended.⁸⁰ The most important advance was the transmission of voice rather than code, something that the electron tube, as oscillator and amplifier, made possible.

One of the engineers who developed radiotelephony for aircraft, A. Hoyt Taylor, recalled some of the problems:

The first time I went up in a plane and listened to signals from the ground, I felt pretty hopeless. The places assigned for the radio operator were in no way shielded from the tremendous noise of the engines. Engine mufflers were not too efficient. In addition to this, the ignition interference from the spark plugs in the engine was terrific. In order to shut out the engine noise we experimented with all kinds of radio helmets, the telephone receivers being buried in the ear caps of the helmet, surrounded with a sponge rubber device, which was supposed to close up the ear against extraneous sound.⁸¹

Work went into ameliorating the interference problem and making a transmitter that would respond well to the human voice, but not to engine or wind noise. Engineers devised a soundproof helmet bearing both microphone and earphone, an antenna system that would radiate effectively but not interfere with tactical maneuvering, and a power supply suitable for the electron-tube circuits. It was necessary to make the set as simple to operate as possible, and the tubes had to be small and rugged, yet capable of mass production.⁸²

The French successfully tested air-to-ground wireless telephony at the battle of Verdun in 1916 and air-to-air telephony at Villacoublay the following year.⁸³ The

⁷⁶ Hartcup, p. 152, and Howeth, p. 189.

⁷⁷ Howeth, pp. 189–191.

⁷⁸ Schwarte, p. 193, 266–268. Some planes were equipped with telephones between pilot and observer, because engine noise made communication between them difficult [Hopkins p. 50].

⁷⁹ Schwarte, p. 267, and von Weiher, p. 47.

⁸⁰ Hopkins, pp. 47, 50.

⁸¹ A. Hoyt Taylor, pp. 66–67.

⁸² Clark.

⁸³ Amoudry, p. 172.

latter use of wireless allowed a group of airplanes to coordinate their actions in the course of a mission; thus the voice-commanded squadron became a new fighting unit.⁸⁴ The Royal Air Force began using interplane communication in 1917. In early 1918 aviation radiotelephones (SCR-67 and SCR-68) began to be produced in large numbers in the U.S.⁸⁵ By the end of the war, wireless communication was generally recognized as having great value for military aircraft.⁸⁶ While pilots in 1915 usually regarded a radio set as an unwelcome nuisance, many in 1919 refused to fly without one.⁸⁷

Aviation presented the greatest need for radio telephony, but sea and ground applications followed quickly. During the war Western Electric produced a small radio telephone (the CW-936) that was used on sub-chasers and destroyers, and this set popularized voice communications in the U.S. Navy.⁸⁸ Toward the end of the war, radiotelephones began to be used in tanks; without them, unplanned mass maneuvers of tanks were not possible.⁸⁹

A contemporary wrote: "... radiotelephone-equipped airplanes closed the control loop and subjected airplane pilots to the same principles of command and control incumbent upon the rest of the Army."⁹⁰ Radio served similarly with ships at sea and tanks on land. On a larger scale, radio combined with other means of instantaneous communication to change forever the nature of military activity. In 1920 Arthur Kennelly wrote:

*Just as a spider on watch at the center of her net, becomes a combined spider and net organization, extended into space as a circular plane surface with physiological and nervous mechanism at the center; so a human being armed with a sufficiently powerful radio apparatus becomes in the same sense, a combined man and ether organization, pervading the whole world, and capable of initiating intelligent response over all the globe.*⁹¹

1.3 EAVESDROPPING

1.3.1 Military Intelligence

Homer's *Iliad*, one of the oldest accounts of war, portrays the use of runners for communications and the practice of infiltrating enemy lines to eavesdrop.⁹² The use

⁸⁴ Kennelly, p. 238.

⁸⁵ Clark.

⁸⁶ Prince, and Hartcup, p. 155.

⁸⁷ Prince.

⁸⁸ A. Hoyt Taylor, p. 64.

⁸⁹ Clark. This difficulty was clearly foreseen by the British Colonel Ernest Swinton, one of the early proponents of the tank [Dupuy, pp. 221–223]. At the battle of Cambrai in November 1917, a few tanks carried radios [Macksey, p. 94].

⁹⁰ Clark.

⁹¹ Kennelly, p. 234.

⁹² See, for example, pages 283, 286, and 336 in Robert Fagles' translation of the *Iliad*.

of radio in war facilitated communications enormously, but it facilitated eavesdropping even more. Wireless, indeed, opened two new windows on the activities of the enemy: messages sent by wireless could be intercepted and interpreted; and infantry units, artillery units, ships, and zeppelins using transmitters could be located with direction-finding antennas even when the messages could not be read. The historian Daniel Headrick has written: “As secret interception and code-breaking were added to the arsenal of the warring powers, a new weapon was forged: communications intelligence. This ... was as important to the outcome of the First World War as the strategies and tactics that were formerly emphasized.”⁹³

All of the belligerents worked to eavesdrop on enemy communications. The British navy, for example, maintained a large network of radio listening stations, and along the Western front the Allies maintained a sequence of such stations at intervals of about 15 kilometers.⁹⁴ Frequently, even wired communications could be overheard. On occasion it was possible to tap directly into an enemy line.⁹⁵ More often, one could pick up a telegraph message or telephone conversation with a receiver of the type used for ground telegraphy, since the signal-bearing wire induced currents in the ground. This became an important use of the ground-telegraphy receivers, and often collecting loops were laid out in the ground as close to enemy communications as possible.⁹⁶ The listening services of the opposing armies were so effective that both the British and the Germans were prompted to develop devices (the Fullerphone and the Unabhorchbare Telegraph, respectively) for sending telegraph signals that could not easily be tapped.⁹⁷

The other new window that radio gave to military intelligence was direction-finding. Radio waves generally travel in straight lines from the transmitter, though, like other waves, they are subject to reflection, refraction, and diffraction. The direction from which they arrive at a remote location can be roughly determined by using an antenna consisting of wire wrapped on the perimeter of a square wooden frame; there is no signal when the antenna is perpendicular to the line of propagation, and maximum signal when the line of propagation lies in the plane of the antenna. (See Figure 1.7.) By taking the bearings of a transmitter at two or more locations, one can then determine its approximate location.

The British had used crystal radio-wave receivers for direction finding, but the availability of electron tubes beginning in about 1914 made the technique much more powerful, since tube receivers were immensely more sensitive. Direction

⁹³ Headrick, pp. 138–139. Perhaps the earliest instance of intercepted radio communications in wartime was the reading by Japanese radiomen of Russian fleet signals during the 1904–1905 war [Dear, p. 626].

⁹⁴ Kennelly.

⁹⁵ U.S. forces used a device called the telautograph that indicated any variations in line conditions, but if a line was tapped skillfully, even with the telautograph it was difficult to detect the wiretap [*Report of the Chief Signal Officer*, p. 243].

⁹⁶ Cusins. A countermeasure was the use of twisted-pair conductor; with ground-telegraphy receivers could read messages from single-wire lines up to a distance of four miles [*Report of the Chief Signal Officer*, p. 115].

⁹⁷ Hartcup, pp. 77–78.

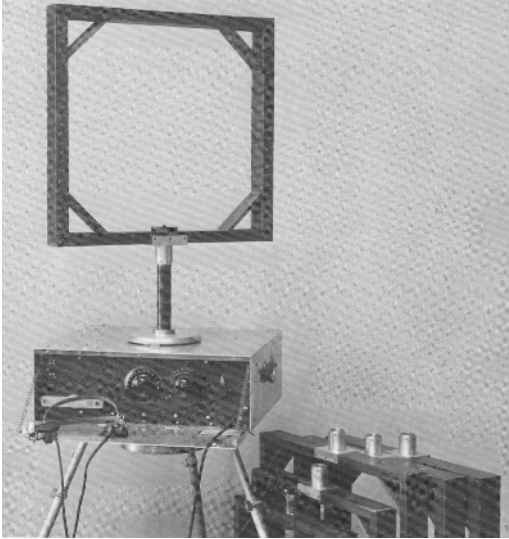


Figure 1.7. Direction-finding antenna (photo courtesy of NIST Boulder Labs).

finding, therefore, grew to be a large branch of military intelligence, one employed almost every place the enemy used wireless transmitters.⁹⁸

The Germans used the technique as early as the first month of the war, following the location of the Russian staff, which was using a transmitter, throughout the battle of Tannenberg.⁹⁹ The French used direction finding to follow the forays of German zeppelins, in particular in warding off such attacks on Paris.¹⁰⁰ It was the British, though, who most effectively employed the technique. Whenever a German surface ship, U-boat, or zeppelin in the North Sea made a radio transmission, it was likely that several British listening stations determined its direction. The information was telegraphed to the Admiralty, where the location of the transmitter was calculated.¹⁰¹ By May 1915 the British were in this way tracking U-boats across the North Sea with an accuracy of about 20 miles.¹⁰² For the Atlantic Ocean, fewer listening stations and greater distances meant that the accuracy was only about 50 miles. Direction finding was thus an effective tool in the fight against the U-boat, and it became especially important after the institution of the convoy system, since evasive routing was then possible (and because the latest information could be supplied to the convoy by wireless).¹⁰³

⁹⁸ Cusins. The first use to which British-army engineers put the triode was in a direction-finding receiver.

⁹⁹ Cusins. According to Cusins, Hindenberg gave some credit for the victory to this employment of the direction-finding technique.

¹⁰⁰ Amoudry, pp. 187–190, and Beesly, p. 141.

¹⁰¹ Hartcup, p. 123.

¹⁰² Beesly, p. 254.

¹⁰³ Beesly, p. 261, and Howeth, p. 210.

The information gathered by direction-finding stations could be used in another way: “traffic analysis”. Even without decrypting enemy messages, one could often deduce much about their activities and intentions by analyzing when wireless transmissions were made, from what locations, and in what numbers. The significance of deviations from established patterns could sometimes be guessed. On many occasions traffic analysis combined with direction finding and cryptanalytic results to give an accurate picture of enemy operations.¹⁰⁴ Of course, if one drew conclusions from radio traffic, one could also be deceived by it. In the summer of 1918 the British increased wireless activity at a position on the Western Front where they wished to make the Germans believe an offensive was imminent, and the deception was reportedly successful.¹⁰⁵

Aviators used direction finding for navigation in two different ways. In the first, the aviator transmitted a coded message identifying himself. Direction-finding stations replied, also in code, giving the bearing of the first transmission. With responses from two or more stations, the aviator could find his position on a map. (The British learned the identifying code of many German zeppelins and were thus helped in tracking zeppelins across the North Sea.) The second way had the advantage that the aviator need not break radio silence, but required direction-finding capability on the plane: the aviator took bearings on two or more transmitters in known locations.¹⁰⁶ Many ships acquired direction-finding sets, which they used to determine their bearings relative to what might be called “radio lighthouses”, stations set up along coasts to broadcast identification signals for navigation purposes.¹⁰⁷ In the 1920s it became usual for ships to have direction-finding sets, and in 1935 it became mandatory for all large ships on the British ship register.¹⁰⁸

During the war Telefunken devised a way for a navigator without direction-finding equipment to determine his bearing relative to a known location. Lighthouses had long provided such a service for mariners; a light flashed when the rotating beam aimed directly north, so that the bearing could be deduced from times from the flash to the passage of the beam and from the passage of the beam to the next flash. Telefunken built a transmitter with 32 directional antennas oriented as the points of a compass. After a start signal, which was radiated from all 32 antennas, the antennas radiated in sequence, one at a time, each for 1 second, moving around the circle from North. The navigator deduced his bearing simply by counting seconds from the start signal to the transmission that was loudest.¹⁰⁹

Heavy artillery use, as we have seen, was often intended to disrupt wired communications. The belligerents sought also to disrupt radio communications by

¹⁰⁴ Morgan.

¹⁰⁵ Terraine 1965, pp. 165–166.

¹⁰⁶ Cusins, and Kennelly.

¹⁰⁷ Kayton.

¹⁰⁸ J.E.D. Williams, p. 184.

¹⁰⁹ J.E.D. Williams, p. 187. After the war improved versions of “wireless lighthouses” were built and operated.

jamming; that is, by sending out strong interfering signals so that enemy messages would be unintelligible. The technique began early in the war, and its use grew as the use of wireless transmissions grew. In the 1918 offensives German jamming stations put out what was described as a “wireless barrage”.¹¹⁰

The enormous efforts made during the war to maintain one’s own wireless communications, to interfere with the enemy’s by jamming, to intercept and decode the enemy’s messages, to prevent the enemy from doing the same, and to use direction-finding to locate the enemy constituted what was called “the wireless war” or “the war of wave lengths”.¹¹¹ This highly technological warfare, where any move might elicit a countermove, resulted in many innovations. Besides the ones already mentioned, there was high-speed automatic transmission of code (regularly used by the Germans and countered by the French using phonographic recording of the transmission) and frequent changes of transmission frequency (used by the Germans and countered by the British with automatic searching devices).¹¹² Of the many intelligence and counter-intelligence activities, the one that attracted the greatest efforts and yielded the greatest returns was cryptanalysis.

1.3.2 Cryptology and the Zimmermann Telegram

In the course of battle, especially early in the war, messages were sometimes sent “in the clear,” that is, without encryption (other than into the dots and dashes of Morse code). Such messages were then almost equally accessible to the enemy. As mentioned earlier, the German victory at Tannenberg owed something to intercepted Russian transmissions, which had been sent “in the clear.” It soon became practice, however, to encode all messages before transmission, and this had the result, not surprisingly, that both sides devoted considerable resources to decoding enemy messages.

Though cryptography (encoding and decoding messages) and cryptanalysis (solving unknown codes) are ancient practices, they first became major government activities with the widespread use of wireless during World War I.¹¹³ The French had for decades cultivated cryptology (the study of cryptography and cryptanalysis) in the Bureau du Chiffre, and during the war they repeatedly broke German codes.¹¹⁴ For example, intercepted information vitally contributed to Allied victory at the Battle of the Marne, which in September 1914 finally stopped the German on-rush a few dozen miles from Paris.¹¹⁵ Other French successes due to intercepted and decoded messages were the capture of the spy Margheretta Zelle,

¹¹⁰ Cusins, p. 769. To overcome the effects of such jamming, the General Electric engineer Ernst Alexanderson devised an antenna system called the “barrage receiver” [Gorowitz, p. II.58].

¹¹¹ The former phrase is Beesly’s, the latter Hartcup’s.

¹¹² Amoudry, pp. 188–189, and Beesly, p. 126.

¹¹³ Morgan.

¹¹⁴ Amoudry, pp. 155–156.

¹¹⁵ Amoudry, p. 154.

better known since as Mata-Hari,¹¹⁶ and a successful counterattack on 18 July 1918,¹¹⁷ that drove the Germans—who had again approached within a few dozen miles of Paris—north of the Marne and marked the final turning of the tide in the war in France.

The British case provides a more typical picture of the status of cryptanalysis in 1914. Early in the war, Admiralty and other wireless stations picked up strange unintelligible messages that were passed on to the Director of Naval Intelligence, Rear-Admiral Henry Francis Oliver. The messages accumulated on Oliver's desk until he chanced one day to talk with Alfred Ewing, Director of Naval Education. Ewing, it happened, cultivated cryptology as a hobby and asked to be allowed to study the messages. Ewing quickly determined that these were German encryptions and was asked by Oliver to set up a department to see if such transmissions could be decrypted.¹¹⁸

The department, which became famous as Room 40, grew in size—by 1917 it employed 800 wireless operators and between 70 and 80 cryptographers and clerks—and delivered valuable information throughout the war.¹¹⁹ The British were extremely fortunate to obtain, in the first months of the war, copies of codebooks for the three principal codes used by the German navy.¹²⁰ Intercepted messages led to the destruction of the German raider *Dresden* on 14 March 1915 and the German collier *Rubens* later that year.¹²¹ An early British naval victory, the battle of Dogger Bank, came about because the German operation order was intercepted and decrypted by the British.¹²² Intercepted messages and direction finding afforded Room 40 knowledge of the number of U-boats at sea and the number in port, as well as approximate positions for many of them.¹²³ According to one historian, radio intelligence was “the most important single factor in the defeat of the U-boats in 1914–18”.¹²⁴ In other ways, too, the work of Room 40 was vital to the Royal Navy's control of the sea routes throughout the war, and without this control, victory by the Allied armies would not have been possible.

In early 1917, Room 40 scored a triumph on the diplomatic front that changed history: it intercepted and decoded—and then shared with the U.S. government—what came to be called the Zimmermann telegram. (See Figure 1.8.) In this communiqué, German foreign minister Alfred Zimmermann proposed that, in the event of U.S. entry into the war, Mexico become an ally of Germany, saying that in exchange for this action Germany would promise a return of the “lost territories” of

¹¹⁶ Amoudry, p. 191.

¹¹⁷ Amoudry, p. 197.

¹¹⁸ Hezlet, pp. 89–90.

¹¹⁹ Tuchman 1958, p. 16.

¹²⁰ Beesly, pp. 3–7.

¹²¹ Beesly, pp. 78–79.

¹²² Hezlet, p. 94.

¹²³ Beesly, p. 91.

¹²⁴ Hezlet, p. 143.

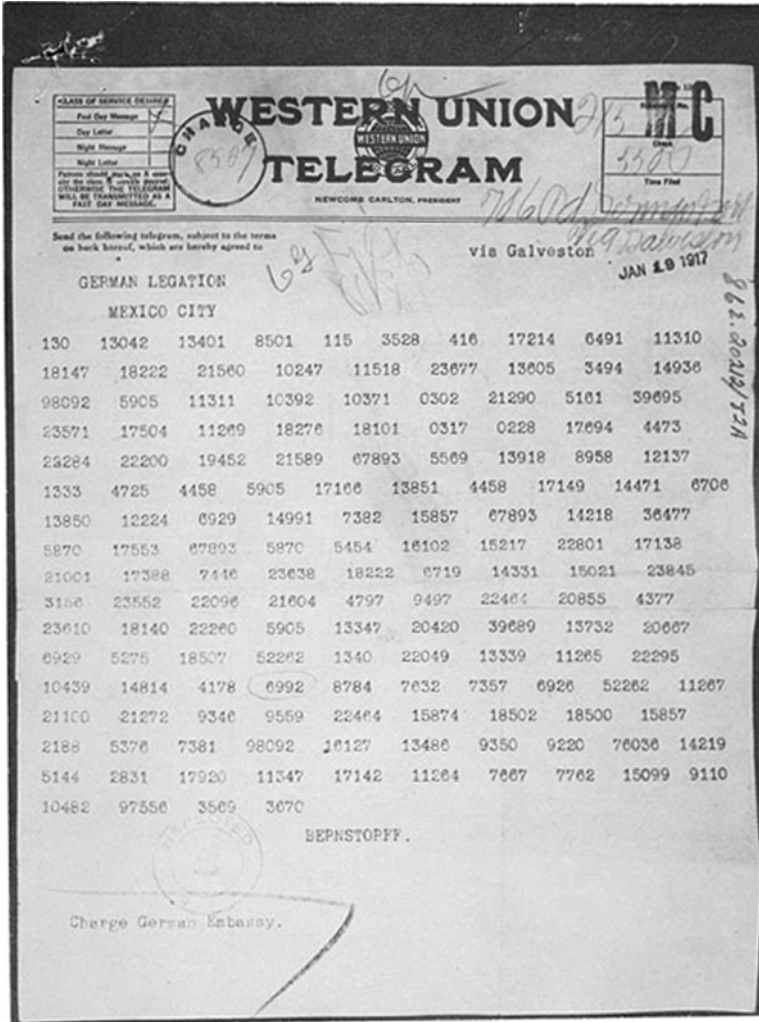


Figure 1.8. A copy of the Zimmermann telegram (photo courtesy of the National Archives).

Texas, New Mexico, and Arizona.¹²⁵ Ray Stannard Baker, Wilson confidant, said of the Zimmermann telegram, “no single more devastating blow was delivered against Wilson’s resistance to entering the war.”¹²⁶ Secretary of State Robert Lansing, who hoped to move public opinion toward support for U.S. entry into the war, said that the telegram “in one day accomplished a change of sentiment and public opinion

¹²⁵ This was, it should be remembered, a time of animosity between the United States and Mexico. On 28 January 1917 U.S. forces under General John J. Pershing were recalled from Mexico, which they had entered seven months earlier in a fruitless attempt to capture the revolutionary and bandit Pancho Villa.

¹²⁶ Quoted in Tuchman 1958, p. 199.

that otherwise would have required months to accomplish.”¹²⁷ Barbara Tuchman wrote:

*Had the telegram never been intercepted or never been published, inevitably the Germans would have done something else that would have brought us in eventually. But the time was already late and, had we delayed much longer, the Allies might have been forced to negotiate. To that extent the Zimmermann telegram altered the course of history.*¹²⁸

Other belligerents also intercepted and decoded enemy messages. Even after the Russians stopped sending wireless messages “in the clear” (which they did for the first year of the war), the Germans succeeded in reading them because they obtained the Russian cipher.¹²⁹ Also, they broke the American cipher used for messages prior to the major assault on the St. Mihiel salient on 12 September 1918, so the Americans found the position largely evacuated.¹³⁰ Yet in the same engagement, a German counterattack on 14 September was repulsed, in part because of foreknowledge gained by the U.S. Radio Intelligence Subsection through decrypting a German message.¹³¹

Later chapters show that governments continued to support cryptologic activities in the years after the war and, at a much higher level, during World War II.¹³² An important consequence for the history of electrical technologies is that these activities played a large role in the development of the modern computer.

1.4 THE ART AND SCIENCE OF RADIO

1.4.1 The Manufacture of Electron Tubes

When war broke out, electron tubes were used as detectors in radio receivers and as repeaters in a few long-distance telephone circuits. When the war ended, tubes performed four essential functions for radio: generating the carrier wave in transmitters, modulating the carrier wave with the audio signal, detecting the signal in receivers, and amplifying signals in both transmitters and receivers. In addition, tubes were used as oscillators in heterodyne receivers, as amplifiers in ground telegraphy and some instruments, and in several other ways (mentioned in Chapter 2).

More striking than the proliferation of uses was the burst in tube production. The total number of audions sold before 1913 was less than 2000; in 1913 sales

¹²⁷ Quoted in Tuchman 1958, p. 199.

¹²⁸ Tuchman 1958, p. 200. U.S. entry into the war was helped by the fact that Russia’s Czarist government was overthrown in March 1917 and replaced by a provisional, ostensibly democratic government; thus the Allies could more plausibly claim to be fighting to save democracy.

¹²⁹ Cruttwell, p. 45.

¹³⁰ Headrick, p. 157.

¹³¹ Morgan.

¹³² The U.S. and French navies had cryptographic departments during the war and retained them after the war; in the 1920s the German and Japanese navies set up cryptographic departments [Hezlet, p. 164].

reached 1700 and in the following year almost 6000.¹³³ By then, of course, the tube had undergone considerable development and other manufacturers had entered the field. French engineers designed an improved version of the audion (with a cylindrical, coaxial arrangement of the electrodes), known as the TM tube (the initials coming from “Télégraphie militaire”). Mass production began in October 1915, and by war’s end more than a million had been made, most of them by Grammont and Compagnie Générale des Lampes, two incandescent-lamp manufacturers.¹³⁴ Because the TM tube was both effective and robust, the British mass produced several versions of it.¹³⁵ By late 1918 many types of radio receiving tubes were being manufactured by several German companies, and a single Telefunken tube (the RE16) was being turned out at the rate of 1000 a day.¹³⁶

Western Electric developed a number of tubes for the U.S. Signal Corps and the U.S. Navy. For example, the 203A (designated the VT-1 by the Signal Corps and the CW-933 by the Navy) was a general purpose tube, used as detector, amplifier, and oscillator.¹³⁷ General Electric was another major U.S. supplier of tubes. GE and Western Electric had agreed to divide the task, GE manufacturing transmitting tubes, Western Electric receiving tubes.¹³⁸ By the end of the war, GE had supplied the military with some 200,000 tubes, and Western Electric had supplied half a million.¹³⁹

For the manufacture of electron tubes it helped enormously that light bulbs had been mass produced for many years. Both devices consisted of metal filaments, with external connections, in an evacuated or gas-filled glass enclosure. But electron tubes were more delicate physically, and their behavior depended sensitively upon the shape and spacing of electrodes, the precise level of vacuum, and the presence of adhering or occluded gases on surfaces within the bulb.¹⁴⁰ Engineers worked out techniques for mass production at the same time other engineers were improving tube design.

In the U.S., AT&T, GE, and Westinghouse made the largest contributions. Westinghouse pioneered high power tubes for radio transmitters.¹⁴¹ In the 1920s both GE and Westinghouse marketed tubes through RCA, which set up its own manufacturing facilities in 1930.¹⁴² The number of tubes made continued to increase; in the United States the production of receiving tubes alone reached 69 million for the year 1930.¹⁴³ In Germany one of the most important tube manufacturers was Siemens &

¹³³ Tyne pp. 108–111, 131.

¹³⁴ Amoudry, p. 167, and Tyne, p. 193.

¹³⁵ Tyne, pp. 200–232.

¹³⁶ Tyne, p. 251.

¹³⁷ Tyne, p. 99

¹³⁸ Hawkins, p. 62.

¹³⁹ Tyne, p. 146.

¹⁴⁰ Fleming 1924, p. 178.

¹⁴¹ Stokes, p. 21.

¹⁴² Stokes, p. 15, and Tyne, p. 308.

¹⁴³ Henney, p. 20.

Halske, where Walter Schottky pioneered the development of multigrid tubes.¹⁴⁴ Whereas Siemens & Halske concentrated on tubes for wire telephony, the other major German tube manufacturer, Telefunken, concentrated on tubes for radio.¹⁴⁵

England in the 1920s had some half dozen major tube manufacturers. Two of the most innovative were Metropolitan-Vickers Electrical Company and Marconi Osram Valve.¹⁴⁶ The latter was formed in 1919 when the Marconi Company and GEC (General Electric Company Ltd., not affiliated with the General Electric company in the U.S.) set up a joint company for the design and manufacture of electron tubes. In the Netherlands, N.V. Philips Gloeilampenfabrieken, a manufacturer of incandescent bulbs, began producing electron tubes in 1917 and soon became an international leader in the field.¹⁴⁷ France in the 1920s had four major manufacturers of electron tubes; particularly innovative was Société La Radiotechnique, which introduced the “azide” or “nitride” process of filament manufacture in 1926 and AC tubes in the following year.¹⁴⁸ In 1931 La Radiotechnique was purchased by Philips. In Japan the Tokyo Electric Company (which after merger with Shibaura Engineering in 1939 became Toshiba) began manufacturing three-element electron tubes in 1917, and already in early 1920 five Japanese companies were in the business.¹⁴⁹

Widespread use of electron tubes received a great boost from the government imposed standardization, all tubes had to be made to the same government specifications.¹⁵⁰ A British engineer commented that during the war the standard triode became: “as much an article of consistent manufacture as a metal-filament lamp.”¹⁵¹ Among all users of tubes, telephone engineers were probably most concerned that tubes be uniform in their characteristics, stable in operation, and long lived. (A long-distance telephone connection might involve more than a hundred tubes, and failure of a single tube could break the circuit.) Bell System engineers—some of them in the engineering department of Western Electric, which manufactured tubes—brought about many improvements. In 1925 the life expectancy of a tube was 50 times that of the early tubes of 1914.¹⁵²

There was, of course, more to the radio art than tube production; transmitters, receivers, power supplies, and antennas also needed to be manufactured. Many companies, typically those already involved in electrical technology, began supplying the rapidly growing needs of the military. The largest French company, the Société française radioélectrique (SFR), like most of the others, adopted the techniques of mass production; by itself during the four years of the war, SFR produced

¹⁴⁴ Tyne, pp. 252–255.

¹⁴⁵ Tyne, p. 431.

¹⁴⁶ Tyne, pp. 373–374, and Thrower, pp. 2–4.

¹⁴⁷ Tyne, pp. 270–271.

¹⁴⁸ Tyne, pp. 398–405.

¹⁴⁹ Okamura, p. 25.

¹⁵⁰ Barnouw, p. 49.

¹⁵¹ Cusins, p. 769.

¹⁵² Fagen, pp. 840–841.

and installed for the Allied armies 63 permanent wireless stations, 300 ship stations, 18,000 airplane stations, and 12,500 mobile stations.¹⁵³ Batteries, which provided the power for radios, were manufactured in huge numbers, more than a million in the U.S. alone.¹⁵⁴

1.4.2 The Science of Electron Tubes

The triode vacuum-tube, which revolutionized 20th-century technology, had a slow start. For six years after its invention in 1906, it was used only as a detector of radio waves, where it was just slightly more effective than the diode tube or a galena crystal.¹⁵⁵ Other applications for the triode—in wired telephony and in wireless communications—began to be found in 1912, but these came only after improvements in the tube design.

Most important was the move from the “soft” tube, containing gas at low pressure, to the “hard” tube, with the enclosed space at high vacuum. De Forest had believed the gas necessary for the tube’s operation. He and others were misled by the fact that when used strictly as a detector of radio waves, the “soft” tube was indeed more sensitive than the “hard” tube.¹⁵⁶ For the tube to function effectively as an amplifier or oscillator, however, a high vacuum was necessary. This was recognized in about 1912 by several engineers working independently: Harold Arnold at AT&T’s manufacturing subsidiary, Western Electric; Irving Langmuir at General Electric; and Alexander Meissner at Telefunken.

Other improvements came rapidly. Harold Arnold devised filaments (of alkaline-earth oxides on a platinum-alloy core) that were much better electron emitters.¹⁵⁷ Better electrode-configurations—such as the cylindrical, coaxial arrangement of the electrodes in the TM tube, mentioned above—were found. Tubes came to be designed for particular applications: for radio reception, for radio transmission, for telephone repeaters, for various types of amplifiers, and so on. A few examples are a double-grid tube designed by Walter Schottky of Siemens and Halske for terminal amplification in telephone circuits, a tube (the EVN129) designed by Telefunken as a heterodyne oscillator, and a tube (the Type E) designed by Western Electric for transmitters in airplanes.¹⁵⁸ For use in aircraft, ships, and other places where mechanical shocks and vibrations were common, “ruggedized” tubes were designed.¹⁵⁹

Some tubes had one or more electrodes in addition to the cathode, control grid, and anode of the audion. In 1913 Langmuir, who had discovered “space charge” (a

¹⁵³ Griset, p. 40, and Libois, p. 53.

¹⁵⁴ *Report of the Chief Signal Officer*, p. 10.

¹⁵⁵ Stokes, p. 8.

¹⁵⁶ Stokes, p. 8.

¹⁵⁷ Smits, p. 134, and Thrower, pp. 28–29.

¹⁵⁸ Tyne, pp. 100, 245, 248.

¹⁵⁹ Fagen, p. 845.

build-up of electrons in the space around the cathode), found he could reduce the space charge, and thus increase gain, by inserting a grid between the cathode and control grid.¹⁶⁰ In 1916 Schottky inserted a grid between control grid and anode in order to increase gain, thus making what came to be called the screened grid tube.¹⁶¹

As these examples suggest, much of the advance came from increased understanding of how the tube functioned. Walter Schottky of Siemens & Halske, G. Stead at the Cavendish Laboratory of the University of Cambridge, Henry J. Round of the British Marconi Company, and Harold D. Brown of Western Electric were leading contributors, but perhaps most influential was Irving Langmuir of General Electric. A Columbia University graduate who obtained a Ph.D. under H.W. Nernst at Göttingen, Langmuir began publication of his studies of vacuum tubes in 1913. His most famous paper, presented to the Institute of Radio Engineers in April 1915, was entitled “The pure electron discharge and its applications in radio telegraphy and telephony”; it made famous the so-called “ $3/2$ power law”.

Walter Schottky published a landmark paper in 1918. It analyzed two basic sources of noise in an amplifying tube: thermal noise (arising from random heat-motion of atoms) and the shot effect (arising from the randomness of emission of electrons from the cathode). In the 1920s Bell System engineers John B. Johnson and Harry Nyquist extended Schottky’s theoretical and experimental work, and such studies enabled engineers everywhere to reduce electronic noise in a great variety of circuits.¹⁶² The Bell System engineer H.J. van der Bijl pioneered in the analysis of tube performance using measurable parameters and in the techniques for designing circuits whose behavior could be predicted from these parameters. His 1920 text *The Thermionic Vacuum Tube and Its Applications* was a widely-used guide to such methods.¹⁶³

Better understanding of the electron emission process and better materials for filaments and filament coatings led an increase in the efficiency of cathode emission by a factor of four in the 1920s.¹⁶⁴ The continued proliferation of tube types yielded tubes well suited to a great variety of tasks. In power output, for example, the tubes of the 1920s ranged from one-hundredth watt (in the miniature or “peanut” tubes used especially in portable devices) to 100 kilowatts (in the large water-cooled transmitting tubes).¹⁶⁵

Wartime urgencies, which brought great human and material resources to the development of wireless communications, resulted in startling technological advances. Other factors contributed. The hindrances of patent claims were swept

¹⁶⁰ McNicol, p. 168, and Thrower, p. 10.

¹⁶¹ Thrower, p. 10.

¹⁶² Fagen, pp. 910–912.

¹⁶³ Fagen, p. 262. In 1920 van der Bijl returned to South Africa, his native country, and played an important part in the technical development of that country.

¹⁶⁴ Fagen, pp. 974–975.

¹⁶⁵ Fagen, p. 841.

aside by government edict.¹⁶⁶ In the U.S., Assistant Secretary of the Navy Franklin Roosevelt told contractors to use any patented invention required, guaranteeing them against claims for government work.¹⁶⁷ The patent moratorium and the fact that almost all radio equipment was manufactured for the military caused companies to concentrate on research and development rather than on litigation or marketing.¹⁶⁸ Technology transfer was facilitated by collaboration by different companies on government orders and by sharing of techniques between allies.

One finds in the writings of engineers who were involved in radio at this time many expressions of how rapid the wartime development was. Arthur Kennelly wrote: “It has been estimated that ... the war advanced [radio communication] more in four years than perhaps might have been accomplished in twenty or thirty years of peace. ...”¹⁶⁹ Less exaggeratedly, George Squier commented on the development of vacuum tubes in the period of the U.S. involvement in the war as follows: “The engineering advancement accomplished in less than two years represents at least a decade under the normal conditions of peace. ...”¹⁷⁰ The British engineer B.S. Gossling wrote:

*The thermionic valve passed during the period of the war through all the various stages of the transition from an instrument the value of which was already recognized, but whose operation was erratic and theory obscure, to a product as reliable and as thoroughly standardized in manufacture as the incandescent lamp, and in addition capable, as regards all the main principles of its action, of explanation in terms of well-established principles of physical science. ...*¹⁷¹

It is important to recall the status of wireless communications before 1914. In 1912 a U.S. court condemned Lee de Forest for “abuse of trust on the basis of valueless patents, in particular a three-electrode lamp called an ‘audion’ which has been proved to be without any interest whatsoever!”¹⁷² At that time electron tubes had found only one use, as a detector of wireless signals, and even in this application other devices, notably crystal detectors, were much more widely used. Wireless technology itself had only limited applications. The historian Howard Aitken has written, “What was the new technology good *for*? Until World War I the answer could without serious error be summed up in two words: ships and lighthouses.”¹⁷³

¹⁶⁶ The most famous example of legal logjam was the ruling in 1916 by the U.S. District Court in New York City that the audion infringed on Fleming’s valve patent, but that the third electrode was protected, so that both patents were required to manufacture triodes [Barnouw, p. 47].

¹⁶⁷ Barnouw, pp. 47–48.

¹⁶⁸ Susan Douglas 1985, p. 169.

¹⁶⁹ Kennelly, p. 245.

¹⁷⁰ Squier, p. 304.

¹⁷¹ Gossling, p. 670.

¹⁷² Quoted in Antébi, p. 125.

¹⁷³ Aitken 1976, p. 306.

Military needs so stimulated radio's development that the years 1914 to 1920 stand out as a distinct phase in its history.¹⁷⁴ This period followed the experimental period from 1886 to 1900 (set off by Hertz's investigations) and the maritime period from 1900 to 1914 (dominated by the Marconi companies, which provided ship-to-shore and ship-to-ship communications), and it prepared the way for the broadcasting period beginning in 1920 (the subject of Chapter 4). Indeed, the technology of broadcasting came directly from wartime work. In the United States most of the early household receivers were copies of ones designed for the military, and early transmitters used the techniques developed for military and other governmental use during the war.¹⁷⁵

1.4.3 Radio Engineers

Radio engineering involved much more than tubes. The most powerful transmitters were Poulsen arcs and alternators. Intense laboratory study by engineers at the Federal Telegraph Company, led by Leonard F. Fuller, resulted in much more powerful arc transmitters; a 100-kW arc was built in 1916 and several 500-kW arcs just two years later.¹⁷⁶ By 1920 some 200 stations were using arcs for transmission.¹⁷⁷ As mentioned earlier, the AC generator, or alternator, was another way to generate continuous oscillations, and alternators were used in some of the most important transmitting stations during and after the war.

There were advances in all facets of radio. Antennas were improved. The U.S. Navy, for example, developed a number of static-reducing antenna systems.¹⁷⁸ Power supplies for radio transmitters and receivers were improved. According to the Chief Signal Officer of the U.S. Army, "Scarcely a single piece of technical apparatus that was regarded as adequate at the beginning of the war is to be found in the Signal Corps equipment at the time of the signing of the armistice."¹⁷⁹ Perhaps most remarkable for the military period of radio development was innovation in transmitting and receiving circuits.

The so-called regenerative circuit was discovered just before the war. In 1912, while working to obtain greater amplification with his audion, Lee de Forest found that when the output of a tube was connected to its input (in order to obtain greater amplification), the tube sometimes produced a howl in his earphones, and he then worked to eliminate the phenomenon. At about the same time, Edwin Howard Armstrong made the same discovery and recognized how important it was that an electron tube could generate oscillations. Indeed, tubes were soon in use in transmitters to generate continuous waves and in receivers as the local oscillator in

¹⁷⁴ Howeth, p. 207.

¹⁷⁵ Howeth, p. 211.

¹⁷⁶ Brittain 1991.

¹⁷⁷ Finn 1967.

¹⁷⁸ Howeth, p. 209.

¹⁷⁹ *Report of the Chief Signal Officer*, p. 9.

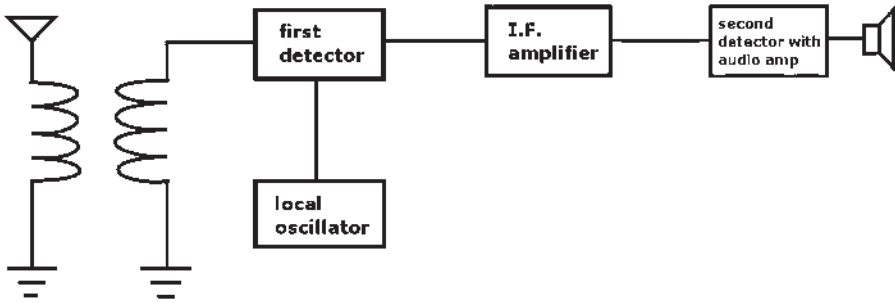


Figure 1.9. The superheterodyne circuit.

heterodyne circuits. Though the arcs and alternators were more powerful, they were much larger and much more expensive than tubes. Moreover, they could not reach frequencies that tubes could, 200 kHz being an upper bound for almost all arcs and alternators. Thus when high-power transmitting tubes were developed in the 1920s, they displaced these devices.

Another great advance was the heterodyne receiver, described above. A refinement of the heterodyne principle was the superheterodyne, invented by Edwin Howard Armstrong while serving in the U.S. Signal Corps in France. Armstrong's idea was to build first a highly efficient fixed-frequency amplifier (at the so-called intermediate frequency), then to tune a local oscillator so that the difference between the incoming frequency and the locally generated frequency equaled the intermediate frequency (which was then produced by heterodyne action). (See Figure 1.9.) In the 1920s it became, and remains today, standard in radio receivers.

Another achievement of this period was the establishment of professional societies for radio engineers. In the first decade of the century, the electric power industry, already large, was still rapidly growing, and power engineers dominated the American Institute of Electrical Engineers (AIEE). Many of those concerned with other types of electrical technology, such as electrochemistry or wireless telegraphy, felt that the AIEE was not serving their interests adequately, and some of them formed new societies. In 1909, in an effort to prevent further splintering of the profession, the AIEE directors decided to promote the establishment of technical committees within AIEE, such as the Electricity in Mines Committee and the Electrically Propelled Vehicles Committee. This organizational innovation succeeded in its purpose, as the technical committees, numbering 13 by 1915 and 51 by 1962, undertook more and more activities for their members.¹⁸⁰

The wireless engineers, however, had already set up their own professional home. In 1912 the Society of Wireless Telegraph Engineers (started in Boston in 1907) and the Wireless Institute (started in New York in 1908) merged to form the Institute of Radio Engineers (IRE).¹⁸¹ The following year *Proceedings of the Institute of Radio Engineers* began publication. With papers by such engineers as Michael

¹⁸⁰ McMahan, pp. 124–127, and Ryder and Fink, pp. 61–62.

¹⁸¹ McMahan, pp. 127–132, and Ryder and Fink, pp. 65–67.

Pupin, Lee de Forest, and Arthur Kennelly in its first year, it quickly became a premier journal of the rapidly developing field. From its beginnings, the profession of radio engineering had an international character. The founders of IRE decided against including “American” in its name, arguing that IRE interests were international in scope, as was radio itself.¹⁸²

Radio engineering, even more than traditional areas of electrical engineering, had close connections with science. Maxwell, Hertz, Lodge, and Fleming were all physicists, and many of the inventors of wireless techniques, such as Lee de Forest and Walter Schottky, had been educated as physicists. The better understanding of electron behavior, as in photoemission or space-charge buildup, was physics of direct relevance to tube design, and engineers made important contributions to this type of physics. Moreover, radio raised new questions for physicists. For example, Marconi’s long distance transmissions, which surprised physicists (who knew that radio waves, like light waves, propagate in a straight line), led to the discovery of a reflecting layer in the atmosphere, soon given the name “ionosphere”. And radio engineering provided new tools for physical investigation, as in the studies of the ionosphere in the mid-1920s by Gregory Breit and Merle Tuve.¹⁸³ Later chapters pick up the story of radio’s growth as a business and a technology and describe its continuing close relationship with science.

¹⁸² Ryder and Fink, p. 66.

¹⁸³ G. Breit and M.A. Tuve (1925), and G. Breit and M.A. Tuve (1926).

