AWA Review

One Hundred Years of Electronic Communications

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ABSTRACT

The essential elements of electronic communications (mainly the LRS Relay and de Forest audion) arrived on the scene in mid- and late 1906. They developed into practical form during the next five or ten years. Over the rest of the Twentieth Century, the vacuum tube (né audion) and transistor slowly displaced a wide variety of mechanical devices for signal generation, signal amplification, and computation. This article provides a perspective of the arrival and triumph of electronic communication and related arts.

Electronic communications is entering its second century, with good prospects for advancements comparable to those of the first hundred years. It is appropriate to take a look back and consider what marvels the science of electronics made possible. At the same time, there is useful insight in considering how far what we view as "communications" progressed without electronic assistance.

A bit of definition is necessary here. Strictly stated, any device that operates by the use of electrons is "electronic." That's not very satisfying for our purposes: under this view, a flashlight is "electronic." A more relevant approach would have it that "electronics" requires a device that can *amplify* through use of electrons. Once such a unit becomes available, one can "obtain gain," build signal detectors that deliver more signal than they're given, make oscillators, and design the digital circuit elements of computers. Incidentally, it matters little whether the electrons in our "gain device" flow in a solid-state material, a vacuum, or a gas. It is also dangerous to ignore fields like radar or computation, which are not strictly "communications" but are intimately related in terms of technology.

Before the electronic inventions that are listed below, physicists and electricians yearned for some practical means of obtaining gain. The earliest demand came from the wireline telephone industry, which could have used electronic assistance almost from the invention of the telephone. There were large service improvements possible, and huge amounts of capital to be saved, by talking more clearly over longer distances with less copper. The emergence of wireless communication 20 years later opened another need that begged to be filled, in covering longer distances with less transmitter power and smaller antennas.

PRE-ELECTRONIC AMPLIFIERS

Huge efforts went into development of devices to generate high-frequency signals, amplify signals of all frequencies, and detect radio emissions. Some of these lasted quite a while into the electronic age. The invention of non-electronic, usually electromechanical, amplifiers was the centerpiece of this work. These devices often carried the name "telephone relay," in analogy with the relays used in telegraphy. Transmission engineers anticipated such a device almost from the start - Thomas D. Lockwood, later the chief patent attorney for Western Electric, published a three-part article on repeaters in *Electrical World* in 1896. These typically relied on an electromagnet fed by the incoming signal, driving a diaphragm that vibrated a mass of carbon granules - effectively a telephone receiver driving a transmitter. The Western Electric (WE) production versions began with a design by H. E. Shreeve from 1903 (Fig. 1). It evolved into the 1A "Repeater" of 1904 (Fig. 2), the 2A "Repeater Cartridge" of 1910 (Fig. 3), and the 3A "Repeater Cartridge" of 1912 (Fig. 4). The early repeaters carried high hopes. The following is a contemporary account of the results of adding one to a moderately long telephone connection:

At the Long Distance Office in Pittsburg, of the A. T. & T. Company, which is called the Brushton Office, at present is installed a "telephone repeater" which has been the result of incessant and studious work of several experts employed by and under the direction of Mr. Hayes of the Engineering Department. Mr. Grace has personally tested this repeater and explained to me about as follows: (On a St. Louis talk, which Mr. Sherwood says is a never a talk - operator repeats.)

> *"Hello Smith!!!! Hello, why I hear you well tonight." "Say that sounds close, doesn't it?" "Well, I never talked so clearly to you before." "Are you really in St. Louis?"* - *whereupon the repeater was cut out - "Hello, Smith!!!" "Hello!!" "Hello!!" "I don't get that." "Where have you gone?" "Hello!!" "Hello!!"*[1]

Despite the enthusiastic review, the poor frequency response and waveform distortion of these devices made them essentially unusable in tandem connection, a requirement for really long telephone circuits. They received only halting commercial use, reaching a mere 41 units in North America as of 1910.

This didn't prevent some use of the receiver-against-transmitter principle. The WE 111A Amplifier was one such device, used in a telephone set to boost the

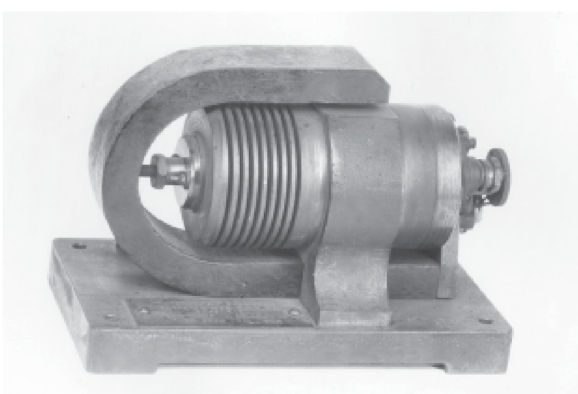

Fig. 1. Developmental Shreeve mechanical repeater, 1904. *Source: Bell Labs, courtesy Jerry Vanicek.*

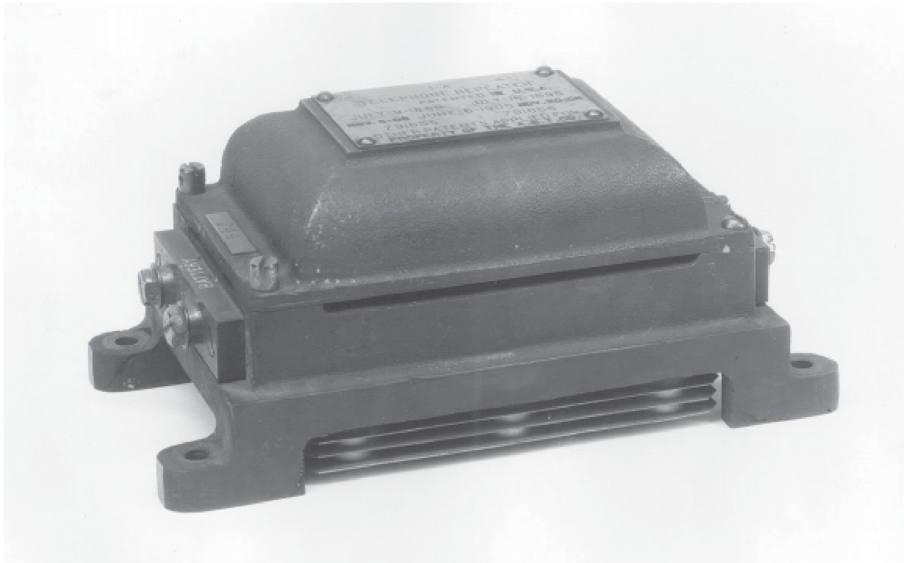

Fig. 2. 1-A developmental "repeater," 1906. *Source: Bell Labs, courtesy Jerry Vanicek.*

received volume. These were being installed as late as the early '60s, but solid-state amplifiers soon replaced them. During the '30s WE made two versions of its "Audiphone" hearing aid. The 36A was simply a carbon microphone driving a headphone. Such an arrangement can provide 20 dB or so of acoustic-to-electrical gain. The 37A and 38A Audiphones were similar, but included a 65A Amplifier giving gain approximating that of one vacuum tube.

In the U. S. amateur-wireless market, there was a "Multi-Audi-Fone" amplifier, offered between 1915 and 1917 and available in one- and two-stage versions able to drive a horn loudspeaker. The Brown Relay from S. G. Brown in the United Kingdom, and a similar version from Siemens & Halske in Germany, were other electromechanical amplifiers.

Fig. 3. 2-A production "repeater cartridge," 1910. *Source: Bell Labs, courtesy Jerry Vanicek.*

One failed attempt to develop an electronic amplifier is notable. Peter Cooper Hewitt, developer of full-wave mercury-arc rectifiers, obtained three U. S. patents (682,695-97) in 1901 for a negative-resistance or "booster" telephone-repeater element for connection in parallel with a telephone circuit. The inherent negative-resistance characteristic of the arc (increasing voltage gives less current flow) might transfer energy

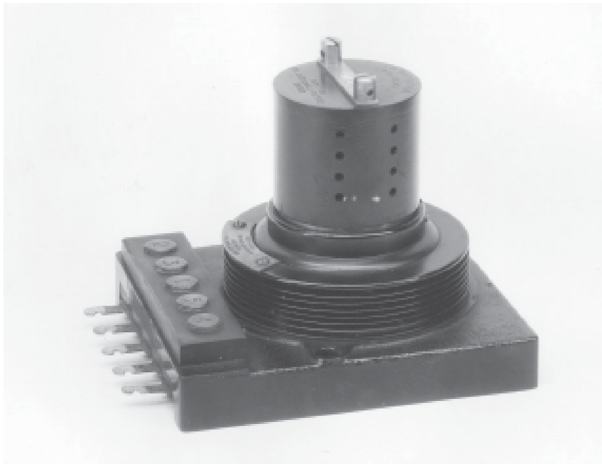

Fig. 4. 3-A production "repeater cartridge," 1912. *Source: Bell Labs, courtesy Jerry Vanicek.*

into the circuit and provide gain. Greenleaf W. Pickard, better known for the Perikon crystal detector, was working in 1904 for the WE engineering department, then in Boston. He tried using a Cooper Hewitt full-wave mercury-arc rectifier as an amplifier. The idea was to strike an arc between the cathode and one of the anodes, then to connect the cathode and the other anode across a telephone circuit. He described the results as "noisy, insensitive".[2]

Another electronic amplifier that failed to work out was a mercury-arc device developed by H. D. Arnold of the WE laboratories about 1912. It used an electromagnet, energized by the incoming signal, to deflect a stream of mercury ions between two auxiliary cathodes. It proved to be noisy, unstable, and short-lived; so the de Forest audion - with some heroic development effort - superseded it before any commercial use (Fig. 5).

PRE-ELECTRONIC RF GENERATORS

While spark-based radio transmitters were the foundation of wireless communication, it quickly became apparent that more effective designs were desirable. The needs were to produce more output for the power fed in, and to occupy less bandwidth on the air. The result was the high-frequency continuous-wave (CW) alternator, as developed by Reginald Fessenden, the General Electric Company (GE), and the Telefunken company in Germany (Fig. 6). It was central to Fessenden's development efforts for the National Electric Signaling Company, ca. 1906, and later formed the core technology of the world-wide radio network of RCA

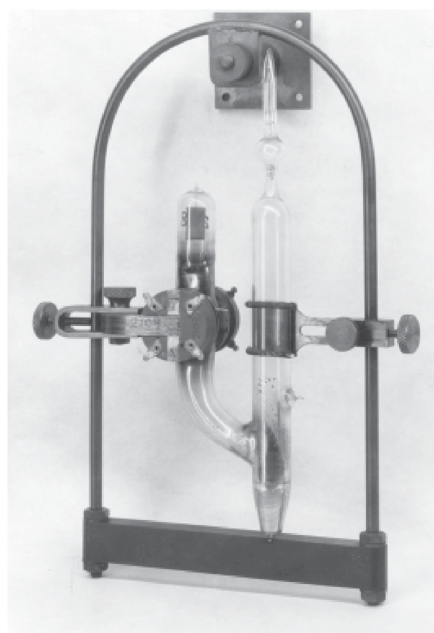

Fig. 5. H. D. Arnold's mercury repeater element in its mounting, with deflection magnets. The active portion is the left arm. *Source: Bell Labs, courtesy Jerry Vanicek.*

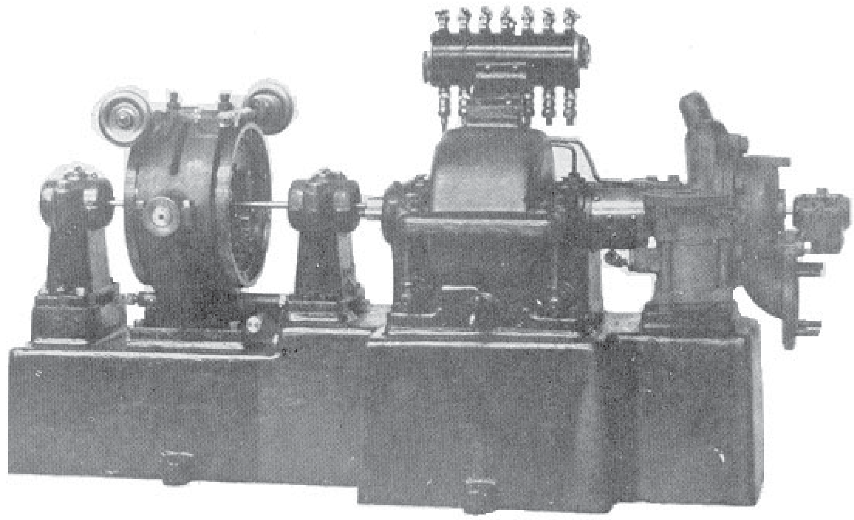

Fig. 6. Turbine-driven alternator built ca. 1906 for National Electric Signaling Co. for marine use (note steam fittings on right). Output was 3 kW at 100 kHz. *Source: Smithsonian Institution annual report, 1908.*

Communications beginning in the early '20s. Alternator stations stayed in regular service into the mid-'40s, and even now the last surviving installation, station SAQ in Sweden, periodically reaches North America with commemorative transmissions. It seems hardly possible to obtain a radio-frequency signal from a rotating machine, but by equipping the rotor with enough poles and rotating it fast enough, frequencies above 20 kHz were obtainable in the GE machines and up to 60 kHz by the Goldschmidt units from Germany, which doubled the generated frequency by using saturable reactors. RCA's machines produced a power of 200 kilowatts with reasonable efficiency.[3]

The other CW signal-generator technology of early times was the Poulsen arc transmitter. This is a quasi-electronic device, since it operates with a plasma of gas ions immersed in a magnetic field. However, it certainly doesn't fit with the electron devices that are known today. Designed in Denmark by Valdemar Poulsen ca. 1910, it was developed in the U. S. in kilowatt sizes by Kilbourne and Clark and the Independent Wireless Telegraph Co. Units up to megawatt level came from the Federal Telegraph Company.[4] European makers included the C. Lorenz Company, Berliner-Poulsen, and Telefunken.[5] Modulated by absorbing some of the output in a carbon microphone, the arc transmitter made possible the regularly scheduled broadcast station SJN in San Jose, California of 1909. The arc effectuated communication between European countries and their colonial possessions: between France and Indochina, and between the Netherlands and Sumatra.

PRE-ELECTRONIC AUDIO GENERATORS

Besides the dramatic high-power rotating signal sources for RF, there were humbler generators for audio. The Bell telephone industry used audio-frequency inductor tone generators in at least three ways. Nearly every telephone central office contained a source of 1000-Hz tone for testing purposes, “the milliwatt,” which appeared as a dial-up number. Its original source was a multi-pole generator turned by a motor running from the 48-volt battery supply. A solid-state replacement became available in the early ’60s, but many of these generators continued in service until much later. In the era of voice-frequency carrier telegraph systems of the amplitude-modulated type (using on-off modulation), it was the usual practice to obtain the carrier tones for the 12 (later 17) channels from a generator that supplied harmonics of 85 Hz (425 through 2295, later 3145 Hz, in 170-Hz steps; Fig. 7.). This practice held from the mid-’20s to the mid-’40s, when tube oscillators became dominant.[6] Finally, the A3 Privacy System, a medium-security scrambler device used on transoceanic high-frequency radiotelephone circuits, got its five carrier tones from a generator that produced harmonics of 550 Hz (3250, 3800 . . . 4900, 5450 Hz).[7] The carriers were used for frequency-shifting slices of the voice spectrum in apparently random order and thus reducing intelligibility to an eavesdropper.

In each of the above cases, an equipment designer made a conscious choice between rotating machinery and tubes, and chose the former. Indeed, in the case of the carrier telegraph system, an earlier, higher-frequency version had used tubes to generate the channel tones, but the new design

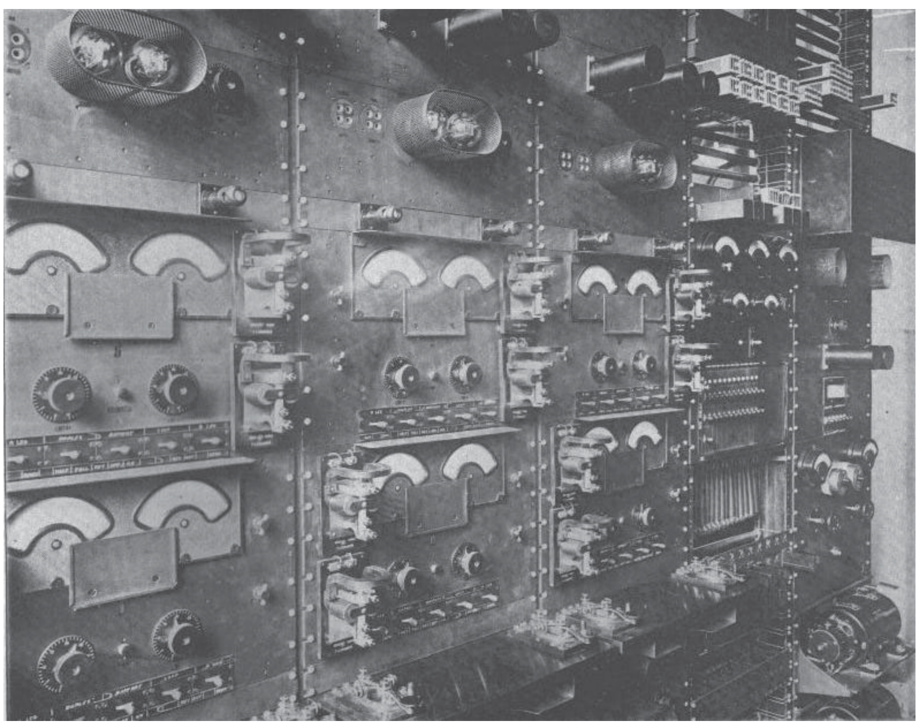

Fig.7. Equipment for six channels (of 12) of a voice-frequency carrier telegraph system, ca. 1925. The rotary tone supply and its backup unit are visible in the extreme lower right. *Source: Western Electric Co.*

went "backward" in its technology.

Extending the "telephone relay" principle, the General Radio Company made a "microphone hummer" consisting of an electromagnet driving a tuning fork. A carbon microphone coupled to the fork picked up its vibrations and fed the magnet, giving an oscillator having good frequency stability (Fig. 8). Versions giving 400 Hz (213-B) or 1000 Hz (213-C) were available beginning about 1930. There was also a unit based on a resonant reed (241-A) for 1000 Hz. Similar units stayed in the GR product line until at least 1951.

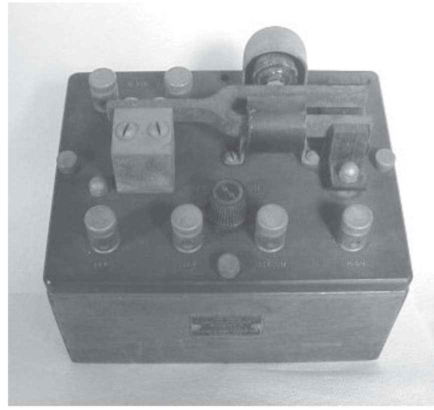

Fig. 8. General Radio "microphone hummer," ca. 1930.

ELECTRONIC DEVICES ARRIVE

The Fleming Valve, a detector diode, appeared in 1905. It certainly operated electronically but couldn't amplify, contrary to the claims of later patent litigators who had tried to make it oscillate. However, it was utterly basic to inventions that followed. Then, four devices with potential for giving gain came onto the scene in 1906.[8]

In March, Robert von Lieben, an Austrian inventor, applied for a patent on the Lieben-Reisz-Strauss Relay. This originated as a magnetically controlled high-vacuum tube, roughly analogous to the General Electric UV-212 of 1920 and the GE 2B23 of 1946. Converted to a grid-control and changed to mercury-vapor fill, the LRS Relay enjoyed considerable success in the 1913-1918 period in audio amplifiers (the Telefunken EV72), RF amplifiers (Telefunken EV75), and heterodyne oscillators for receiving CW radio signals (Telefunken ER75).[9,10] (Figs. 9 - 11). The German Post Office made sizable use of it in repeaters in its long-distance network. It enabled Berlin-Istanbul telephone service in 1915. It served as the nucleus of a 20-watt radiotelephone transmitter,[11] and could oscillate at "wave lengths as short as five or ten meters."

Fig. 9. Two LRS relays in modern times. *Source: Jerry Vanicek.*

In October, the Germans Max Dieckmann and Gustav Glage made application for a patent covering

Fig. 10. Telefunken EV75 high-frequency amplifier, 1913. The EV72 audio amplifier had the same appearance, less the slide rheostat at the right and the circular assembly at the base of the tube. *Source: Telefunken catalog.*

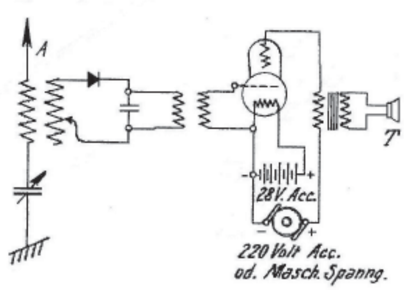

Fig. 11. Basic receiver using an LRS audio stage. (*Source: adapted from Pichler.*[9])

a vacuum magnetic-deflection amplifier. It was a cathode-ray tube like those found today, but having output anodes on the inside of the "screen." The incoming signal deflected the beam magnetically between the anodes, yielding a push-pull output. While probably amplifying successfully, it apparently did not receive commercial use.

In November, Dr. Lee de Forest sought a patent on a gridless tube having a filament, a control anode, and an output anode. As proposed then, it probably would have repeated the input signal but without giving useful gain. However, Heintz & Kaufman Ltd. commercialized this format in "Gammatron" transmitting (and even receiving) tubes in the early '30s. In 1943-44 the Eitel-McCullough Co. experimented with four developmental power tubes of Gammatron form, up to one-kilowatt level.[12]

Also in November, de Forest ordered the first samples of the gridded Audion from his supplier H. W. McCandless, and had them working in the laboratory in late December (Fig. 12). He filed for a patent in early 1907 and received it in 1908. He originally saw it only as a detector-with-gain, but 1912 he and his associates found that the same device was capable of amplifying.

So, by the end of 1906 the possibility of "electronics" had become real.

TELEPHONY: THE "KILLER APP"

It is possible to argue that the telephone industry - taken in any large country in the world - was a more fruitful application for electronics than early wireless communication. Particularly in North America, the telephone business involved far more capital investment than the fledgling wireless trade and, even in the pre-1910 era when telephones were relatively scarce, had more daily impact on the life of the citizenry.

To make this clear, it is necessary to go into a bit of long-distance telephone technology, particularly as practiced in the AT&T /Bell System environment in the U. S. and Canada. It became clear early on that the transmission

Fig. 12. First form of the gridded Audion, possibly the version that was in test in Dec. 1906. *Source: ultimately unknown, but this retouched print is from De Forest Radio Co. files, ca. 1931.*

losses of iron wire were unacceptable for long distances, and that copper wire of large size (up to 165 mils' diameter) was indispensable. The result was New York - Chicago telephone service as of 1893. It was unaffordable to go to thicker wire, at a time when the current commodity price of copper was so important that weekly industry magazines like *Telephony* featured copper quotations on their front covers.

A sizable advance was the invention of the "phantom" circuit. Here two pairs of wire could yield three circuits via the introduction of one-to-one transformers (repeating coils). Two of the circuits were the "physical" or "side" circuits. The third or "derived" circuit involved using the longitudinal path of each of the side circuits via center taps on the side-circuit repeating coils. The four wires were termed a "phantom group." (The very name "phantom" is an index of the wonderment with which early telephone people viewed the idea.) The phantom circuit enjoyed twice as much copper as the side circuits, and so had somewhat less transmission loss (Fig. 13).

The next advance in the pre-electronic era was the invention of "loading," almost simultaneously by George A. Campbell of the AT&T laboratories and Prof. Michael Pupin of Columbia University. Pupin obtained patent protection, and AT&T quickly acquired rights to this invention. The principle of loading was to insert additional inductance in series with the wire, thereby offsetting the undesirable effects of the shunt capacitance. On overland lines, loading was a matter of inserting discrete inductors at fixed intervals along the line. In the case of a "phantomed" line, it became possible to make a triple loading-coil unit that added inductance to both the side circuits and the phantom path. The extra inductance tripled the characteristic impedance of the line, making it more sensitive to leakage across wet insulators, but that was unavoidable.

Loading worked on both open wire and cables. Phantom operation in cables required twisting two pairs of wire together into a "quad" to avoid crosstalk with other pairs

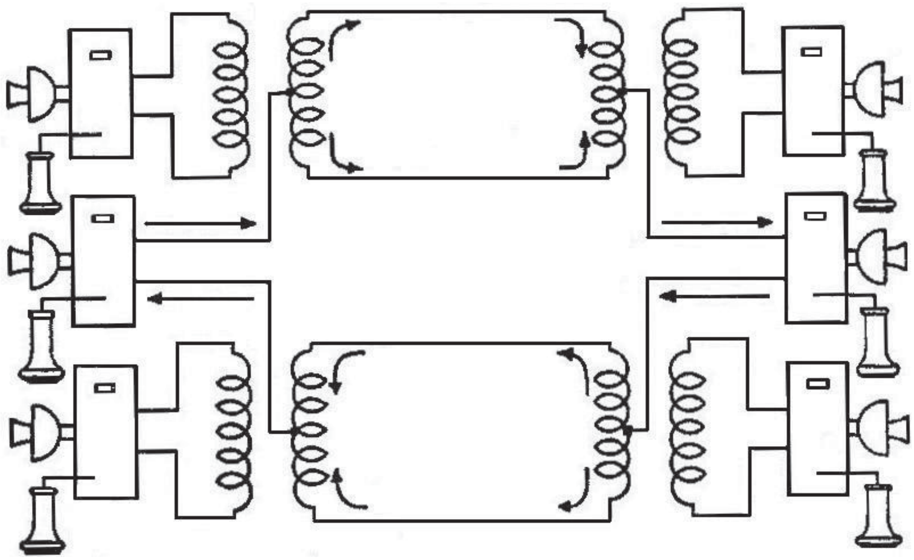

Fig. 13. Basic "phantom group." In practice, four ground-return telegraph channels were derived in addition by adding low-pass filters and blocking capacitors. Ringing between switchboards used a 135-Hz AC signal on each circuit so as not to interfere with telegraph.

in the cable. Loading made possible the construction of a "stormproof" Boston - New York - Philadelphia - Washington cable by 1913. With extraordinarily coarse cable (10- and 13-gauge) and phantom operation, Washington -New York service was possible without a repeater. Extension to Boston required one repeater (Fig. 14).

The same technology let AT&T extend its open wire westward, reaching Denver by 1911. (The official story is that this was the farthest expansion, but there are signs that the company stretched a bit more and reached Salt Lake City, at least on a dry day.) But that was the absolute limit of practical service without multiple gain devices: studies indicated that it would be possible to reach the West Coast without repeaters, but only by using 220-mil wire (or actually copper rod), an unaffordable choice at 774 pounds per mile per wire.

In 1912 de Forest, having discovered that his audion was good for amplifying as well as detecting, sold telephone-repeater rights in his patents to AT&T. This was the "inertialess," relatively distortionless device that had eluded earlier researchers. There was talk at the time to the effect that the Bell System was prepared to pay a million dollars for such a device. De Forest realized $50,000 at the time, plus $340,000 a few years later, for audion rights. He was somewhat ungracious about the $50,000 in his autobiography, terming it "however small . . . a morsel of food for a starving man." Yet that figure was, in terms of today's money, about a million dollars - not a bad return for rights to a device as immature as the audion - gassy, unstable, short-lived, and a severe distortion generator before discovery of the quality-improving properties of negative grid bias.

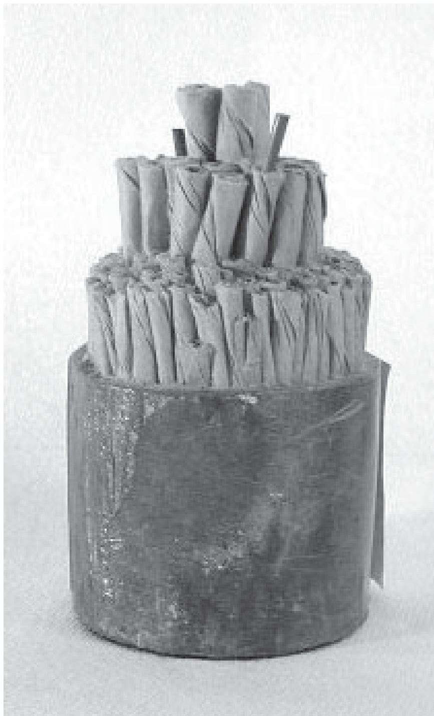

Fig. 14. A slice of the New York - New Haven "B" cable, placed in 1914 to reinforce the New York - Boston route. Wires are insulated with paper strip. Composition is seven quads of No. 10, 18 quads of No. 13, six pairs of No. 13, and 18 pairs of No. 16. Circuit capacity with phantoming is 99 circuits. *Sample courtesy Dan Harley.*

In any event, it was now possible to plan transcontinental telephone service. Construction of a new phantom group to close the transcontinental gap began in 1913 between Denver and Oakland. This required a new pole line across Nevada and Utah, on which the four wires were the sole facility for most of the distance. The new circuits were ready for test in July, 1914, and commercial service began in January, 1915. There was no New York - San Francisco circuit as such; a connection between those places would be "built up" by switching at two or three intermediate points like Pittsburgh or Chicago.

The circuits initially had repeaters at Pittsburgh (Brushton), Omaha, and Salt Lake City (Fig. 15). All three types of repeater - mechanical, mercury-arc, and tube - were tried, with the best results coming from the tube units. After several weeks, repeaters were added at Chicago (Morrell Park), Denver, and Winnemucca (Nevada). In 1920 the loading coils were removed to improve transmission performance, the added attenuation being made up by adding six new repeater points.

This was not an inexpensive project: even including the cost reduction from phantom operation, a New York - San Francisco connection occupied 940 tons (125 cubic yards) of copper and about 168,000 glass insulators.

The success of tube-based repeaters led to their wide installation: by 1919 the total in service in the U. S. was about 1000. Many of these, perhaps 40%, were not associated with a specific telephone circuit. Instead, they were "cord circuit" units, associated with a pair of cords on a telephone switchboard at an intermediate point. The operator, in following routing instructions to "build up" an overall connection, would use ordinary cords or a cord-circuit repeater as directed.

The audion needn't have been the device chosen for transcontinental service. The Lieben-Reisz-Straus group had tried to interest AT&T in the LRS Relay in early 1913, without success. However, if de Forest hadn't preceded them, the LRS Relay could have become the standard repeater device under Western Electric manufacture. It could have also taken a place in the North American "wireless" world.

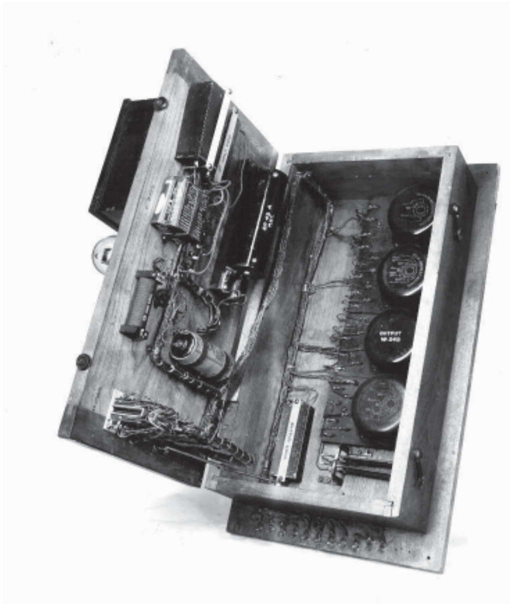
Fig. 15. The interior of one of the repeater cabinets of the type used at Brushton in 1915. See Tyne[8], p. 93, for a front view. *Source: Bell Labs photo, courtesy Jerry Vanicek.*

WIRELESS

While electronic amplifiers were a make-or-break proposition for long-distance telephony, they were "merely very helpful" for radio communication. It is surprising how successful radiotelegraphy was in the absence of electronics. Spark transmitters and passive (e. g., crystal) detectors made for a workable system, in the company of very large antennas and young operators who had good hearing. It was helpful that most radio communication before perhaps 1915 was over salt water, which affords ground-wave propagation far better than over land, and that the frequencies were low (typically 20 to 1000 kHz). Coastal stations appeared in great numbers, making the distance that had to be covered often 200 miles or less.

Even when tube amplifiers began to become common during World War One, passive detectors continued to proliferate. An example would be direction of artillery fire from an observation aircraft, using a BC-15 spark transmitter and BC-14 ground receiver. The entire class of military "pack sets" of the 1910-1919 period appear to have been spark-and-crystal designs.[13] Tube receivers, however, were essential in any case where the antenna had to be small (particularly in direction finders) or where ambient acoustical noise was large (especially aircraft installations). Tube transmitters won out, in large part because of their small signal bandwidth. Arc transmitters, although successful in the 1915-20 era, had a specific problem: while they generated a "CW" signal (with large amounts of phase noise), they offered little suppression of harmonic frequencies. Worse, since keying of the larger units required keeping the arc running and shifting the frequency, they put out *two* sets of interfering harmonics.

Crystal receivers retained a niche use into the '40s, as emergency receivers on ships and lifeboats. Examples include the RCA Radiomarine AR-8503 (a tube set with crystal option), the RCA Radiomarine Type B, and the Federal 123B.

NON-ELECTRONIC RADAR

The common view of radar is that it originated in the '30s, when the tube art was advancing rapidly. However, a radar of sorts existed far earlier. In 1904, Christian Hülsmeyer of Düsseldorf demonstrated, and received patents on, his Telemobiloskop, a device for detecting ships in fog.[14] His system used the wireless technology of the time: a quenched-gap transmitter, a rotating horn antenna, a separate receiving antenna moving with the transmitter, and a coherer detector. It operated at VHF, at frequencies variously estimated as 30 to 600 MHz. The device reportedly detected ships at distances up to 3000 meters. A later development allowed rocking the antennas, thereby measuring the vertical angle of the received echo and allowing a crude estimate of distance. His system therefore satisfied the basic definition of *RA*dio *D*etection *A*nd *R*anging. Sadly, he was unable to interest investors in backing further development.

INDUSTRIAL ELECTRONICS

Electronic principles greatly extended the span of application of electrical methods in manufacture and transportation, slowly dominating the field as development progressed.

One example is that of selective heating of materials in manufacturing. The first important user of radio-frequency heating was probably the tube industry itself. The making of developmental tubes of pre-World War One vintage used wire anodes, with both ends of the wire brought outside the bulb to allow heating by passing a current through the anode. Manufacture also used a direct-current "bombardment" technique (heat the filament, apply a vigorous plate voltage). The goal was to heat the internal elements of the tube to drive out unwanted gases during vacuum pumping and sealing-off. Mass production of tubes as of World War One relied instead on passing the tube through a series of coils with high-frequency current flowing, thereby inducing large heating currents in the tube elements. The source of the current in the early '20s was usually a quenched-gap spark oscillator, typically in the 40-50 kHz range. Tube-based oscillators came later (Fig. 16).

Perhaps a comparison of the operation of tubes in a broadcast station vs. that in industrial heating will show why tubes came into

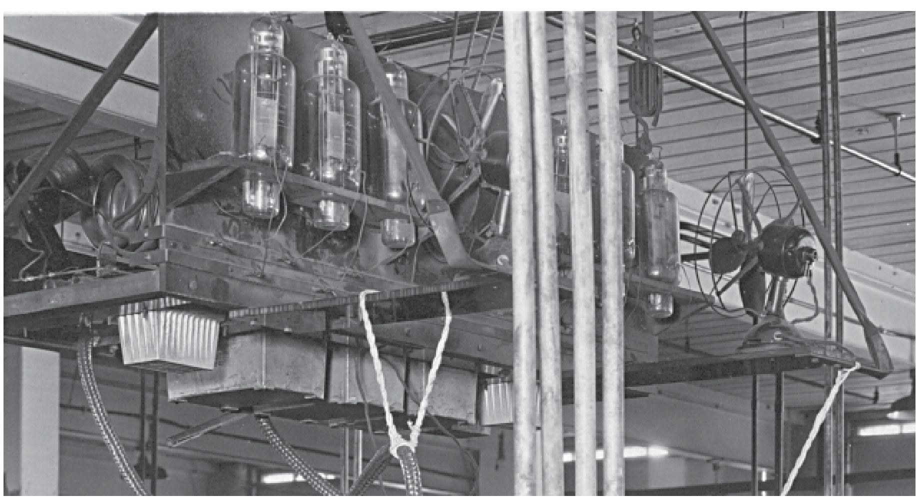

Fig. 16. An RF-heating "bombarder" in the exhaust-and-sealing area of the De Forest Radio Co. tube plant, ca. 1930. It uses six De Forest Type 500 triodes for perhaps 3 kW output. The immense copper-tubing tank coil visible at left suggests operation at a frequency of several MHz. Note use of table fans for air-cooling. *Source: Robert Lozier.*

use only slowly. In typical broadcast practice, the transmitter was turned on once a day. It was in a relatively hospitable location as regards heat, vibration, and swings in supply voltage. It was a matter of engineering pride (and good relations with upper management) to extract long life from the tubes. Transmitters located outside cities, before the advent of remote control, were tended by a skilled operator whose main job was to observe and make adjustments for favorable operation.

By contrast, in typical industrial-heating service the heater would start up many times an hour. The environment might be hot, dusty, and vapor-filled. Portable heaters received the shock and vibration of being moved around the plant. The load on the oscillator varied widely, depending on the placement of the heating coil(s) and the work, and on the point in the heating cycle. The heater(s) would receive minimal attention from the plant electrician, who had to attend all the other equipment in the place. A quenched-gap oscillator, although requiring periodic cleaning of the gap, was suitably simple and rugged. One major maker, Lepel High Frequency Laboratories, advertised a line of quenched-gap oscillators as late as 1938 (Fig. 17).

The situation evolved in later years, especially after the widespread adoption of high-frequency heating to speed production in World War Two. Not long after, tubes optimized for heating use became available, with extra-thick copper anodes to store heat during the unfavorable part of the heating cycle, grids rated to dissipate unusual amounts of power, rugged construction, and thoriated-tungsten filaments to improve efficiency over that of pure tungsten.

There are numerous other uses of high-frequency heating: skin-hardening of gear teeth, automatic soldering and brazing, welding of plastics, etc. The latter requires multi-megahertz frequencies that quenched-gap oscillators (or motor-generators or mercury-arc converters) cannot reach. The "universal" use of high-frequency heating today is the magnetron-powered microwave oven.

Another slow incursion of electronics was in the area of theater light dimming. The simple rheostat dimmers of the earliest days yielded to saturable reactors (magnetic amplifiers), in which an inductor wired in series with the lights received a variable magnetic field from a direct current flowing in a second winding on the inductor core. From the '30s on (e. g, Radio City Music Hall), these non-electronic systems served reliably. Only with the arrival of silicon controlled rectifiers (SCRs) in the early '60s did electronics really take over.

Magnetic amplifiers had other applications. They enjoyed a sort of golden age in the '50s, in which their simplicity, ruggedness, and small size - and the arrival of high-efficiency core materials - made them attractive for control-system applications in aircraft and military systems. The eventual maturing of transistor and SCR technology largely displaced them.

There are numerous other applications of industrial electronics - photoelectric control, variable-speed drive of motors, welding controllers, etc. - which became possible as electronics came of age.

COMPUTATION

The science of computation was relatively late in receiving the benefits of electronics. Punched-

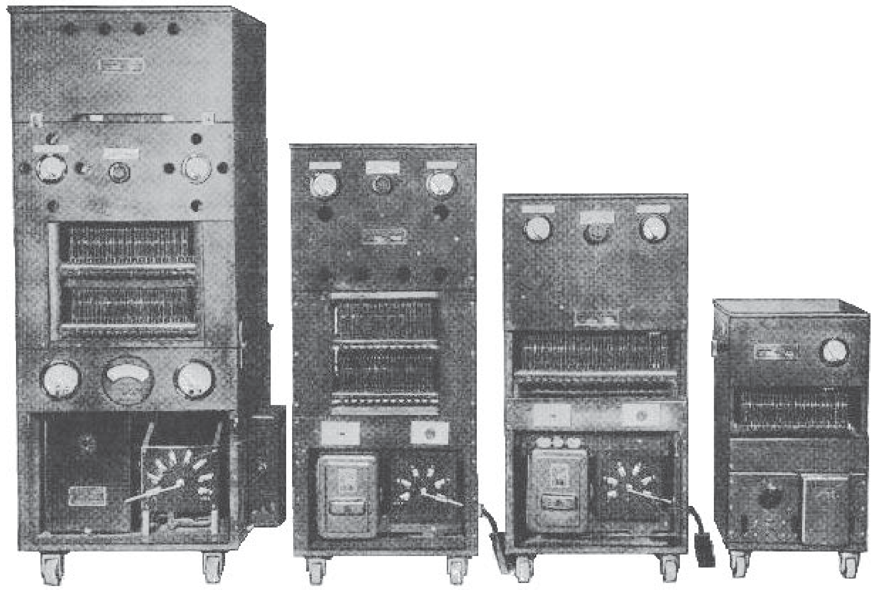

Fig. 17. The Lepel product line of quenched-gap RF "bombarders." The smallest unit operated with input power of five kW. Source: Ad in *Electronics*, June 1930.

card accounting systems capable of sorting, calculating, summarizing, and printing became highly sophisticated from their introduction ca. 1890 to their highest development in the '60s. Analog computers for direction of naval gunfire, using input/output shafts, precision gears, and finely machined cams, attained great precision at the time of World War Two and stayed in use throughout the big-guns era. These grew in capability to give ever more precise firing solutions by including subtle variables like the temperature of the gun and its powder, the degree of wear of the barrel, and the strength and direction of winds aloft. In the beginnings of digital computation, between 1937 and 1946, Bell Laboratories built six models of computer that used telephone relays and crossbar switches, with punched-tape and teletypewriter input-output. The largest used 9000 relays. Some of these installations stayed in use into the '60s. Eventually tubes became attractive for computer systems, such as the Electronic Numerical Integrator and Calculator (ENIAC). It used 6,550 6SN7GTs, 4,200 6L6s, 2,600 6SA7s, and so on. Computers were a major impetus for development of long-life tubes and, in military use, subminiature types.

CRYPTOGRAPHY

The enciphering and deciphering of messages was a relatively late use of electronics. Paper-and-pencil methods, mechanical "cipher machines" (e. g., the U. S. M309 Converter) and electromechanical encipherment systems, e. g., Enigma) largely held the field until the '50s. One of the high-level Japanese encipherment systems of World War Two relied, quite sensibly in terms of manufacture, on a group of 26-position rotary telephone stepping switches. Even automatic on-line cryptography could be done without electronics. One such case was the Vernam (AT&T) cipher system of World War One, in which the plain text is punched into paper teletypewriter tape. Another tape contains the non-repeating encipherment key. An "exclusive-or" logic function using ordinary telegraph relays combines the message and key into the encrypted signal to go out on the line or radio channel. A similar process at the receiving end extracts the message from the incoming signal.

The British "bombe" of World War Two for decrypting intercepted German messages enciphered with the Enigma machine (using the 4313A trigger tube) was the first important use of electronics in cryptography. Postwar vacuum-tube computers became important in the early '50s, ultimately followed by the universalization of cryptography in personal computers.

CONCLUSION

It has been a long path from nonelectronic telephony and wireless to digital signal processors, fiber-optic transmission, and similar marvels. We are now in the second century of that journey.

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