1

A BRIEF HISTORY OF MICROWAVE RADIO FIXED POINT-TO-POINT (RELAY) COMMUNICATION SYSTEMS

1.1 IN THE BEGINNING

Message relaying and digital transmission seem like recent inventions. Not true—these go way back. The first known message relay system was created by the Egyptian king Sesostris I about 2000 BCE. The earliest recorded digital relay transmission by electromagnetic means was around the same time during the Trojan War. King Agamemnon and his troops used signal fires located on mountaintop repeater stations to communicate with each other. The king even used that method to send a message to his wife Clytemnestra. The binary message was either the war was continuing (no fire) or the war was over and he was returning home (fire). The Greek general Polybius, in 300 BCE, developed a more complex message set to allow greater information transfer per transmitted symbol. One to five torches were placed on top of each of two walls. Since each wall had five independent states, this allowed 24 Greek characters plus a space to be transmitted with each symbol. This basic concept of using two orthogonal channels (walls then and in-phase and quadrature channels today), with each channel transmitting independent multiple digital states, is the basis of the most modern digital microwave radio systems of today (Bennett and Davey, 1965).

Digital transmission systems continued to advance using the basic concept developed by Polybius. Systems used in the eighteenth and early nineteenth centuries were direct descendents of this approach. In 1794, the French government installed a two-arm optical system, developed by the Chappe brothers 2 years earlier, which could signal 196 characters per transmitted symbol. This system used several intermediate repeater sites to cover the 150 miles between Paris and Lille. In 1795, the British Admiralty began using a 64-character dual multiple shutter optical system. Versions of this semaphore system are in use in the military today (Bennett and Davey, 1965).

Synchronous digital transmission began in 1816 when Ronalds installed an 8-mile system invented by the Chappe brothers. Each end of the system had synchronized clocks and a synchronized spinning wheel that exposed each of the letters of the alphabet as it spun. At the transmitting end, the operator signaled when he or she saw the letter of interest. At the receiving end, a sound (caused by an electric spark) signaled when to record the exposed letter (Bennett and Davey, 1965).

Sömmering proposed a telegraphic system in 1809. Wire (cable)-based electromagnetic telegraphic systems began in the early 1800s with the discovery of the relationship between electricity and magnetism by Aepinus, Oersted, Ampère, Arago, Faraday, Henry, Ohm, Pouillet, and Sturgeon and chemical

Digital Microwave Communication: Engineering Point-to-Point Microwave Systems, First Edition. George Kizer.

batteries by Volta, Becquerel, Daniell, Bunsen, and Grove (although a chemical battery from 250 BCE was discovered in Baghdad, Iraq, by Konig in 1938). In 1886, Heaviside introduced the concept of impedance as the ratio of voltage divided by current. In 1892, he reported that an electrical circuit had four fundamental properties: resistance, inductance, capacity, and leakage. In 1830, Joseph Henry used an electromagnet to strike a bell over 1 mile of wire. In 1834, Gauss and Weber constructed an electromagnetic telegraph in Gottingen, Germany, connecting the Astronomical Observatory, the Physical Cabinet, and the Magnetic Observatory. In 1838 in England, Edward Davy patented an electrical telegraph system. In 1837, Wheatstone and Cooke patented a telegraph and in 1839 constructed the first commercial electrical telegraph. Samuel Morse, following Henry's approach, teamed with Alfred Vail to improve Morse's original impractical electromagnetic system. The Morse system, unlike earlier visual systems, printed a binary signal (up or down ink traces). Vail devised a sequence of dots and dashes that has become known as *Morse code*. Morse demonstrated this system in 1838 and patented it in 1840. This design was successfully demonstrated over a 40-mile connection between Baltimore and Washington, DC in 1844. About 1850, Vail invented the mechanical sounder replacing the Morse ink recorder with a device allowing an experienced telegraph operator to receive Morse code by ear of up to 30 words per minute. Morse and Vail formed the Western Union to provide telegram service using their telegraphic system (Carl, 1966; IEEE Communications Society, 2002; Kotel'nikov, 1959; O'Neill, 1985; Salazar-Palma et al., 2011; Sobol, 1984; AT&T Bell Laboratories, 1983).

While the early systems were simple optical or sound systems, printing telegraphs followed in 1846 with a low speed asynchronous system by Royal House. In 1846, David Hughes introduced a high speed (30 words per minute) synchronous system between New York and Philadelphia. Gintl, in 1853, and Stearns, in 1871, invented telegraphic systems able to send messages in opposite directions at the same time. In 1867, Edward Calahan of the American Telegraph Company invented the first stock telegraph printing system. In 1900, the Creed Telegraph System was used for converting Morse code to text.

Soon systems were developed to provide multiple channels (multiplexing) over the same transmission medium. The first practical system was Thomas Edison's 1874 quadruplex system that allowed full duplex (simultaneous transmission and reception) operation of two channels (using separate communications paths). In 1874, Baudot invented a time division multiplex (TDM) system allowing up to six simultaneous channels over the same transmission path. In 1936, Varioplex was using 36 full duplex channels over the same wire line. Pulse code modulation (PCM), the method of sampling, quantizing, and coding analog signals for digital transmission, was patented in 1939 by Sir Alec Reeves, an engineer of International Telephone and Telegraph (ITT) laboratories in France. In the 1960s, PCM telephone signals were time division multiplexed (TDMed) to form digital systems capable of transmitting 24 or 30 telephone channels simultaneously. These PCM/TDM (time division multiplex) signals could be further TDMed to form composite digital signals capable of transmitting hundreds or thousands of simultaneous telephone signals using cable, microwave radio, or optical communications systems (Bryant, 1988; Carl, 1966; Fagen, 1975; Welch, 1984).

From 1847, wire-based terrestrial systems were used on oversea cables beginning in 1847. These long systems could not use repeaters and were quite slow (about one to two words per minute). The use of Lord Kelvin's mirror galvanometer significantly increased transmission speed to about eight words a minute. Basic transmission limitations were analyzed using the methods of Fourier and Kelvin. In 1887, Oliver Heaviside, by analyzing the long cable as a series of in-line inductances and parallel resistances, developed a method of compensating the cable to permit transmission rates limited only by loss and noise. Distributed inductors (loading coils) were patented by Pupin in 1899 and further developed by Krarup in 1902. By 1924, distributed inductance allowed the New York to Azores submarine cable to operate at 400 words per minute (Bryant, 1988; Carl, 1966; Fagen, 1975).

About 585 BCE, Thales of Miletus discovered both static electricity (attraction of dry light material to a rubbed amber rod) and magnetism (attraction of iron to a loadstone). In 1819, Hans Orsted demonstrated that a wire carrying electric current could deflect a magnetized compass needle. Wireless transmission, utilizing orthogonal electric and magnetic fields, began in 1840 when Joseph Henry observed high frequency electrical oscillations at a distance from their source. James Maxwell, besides making many contributions to optics and developing the first permanent color photograph, predicted electromagnetic radiation mathematically. He first expressed his theory in an 1861 letter to Faraday. He later presented his theory at the Royal Society of London in December 1864 and published the results in 1873. His theory can be expressed as four differential or integral equations expressing how electric charges produces electric fields (Gauss' law of electric fields), the absence of magnetic monopoles (Gauss' law of magnetism), how changing magnetic fields produce electric fields (Faraday's law of induction), and how currents and changing electric fields produce magnetic fields (Ampere's law). The modern mathematical formulation of Maxwell's equations is a result of the reformulation and simplification by Oliver Heaviside and Willard Gibbs. Heinrich Hertz (an outstanding university student and an associate of Helmholtz) demonstrated the electromagnetic radiation phenomenon in 1887. In 1889, Heinrich Huber, an electric power station employee, questioned Hertz if radio power transmission between two facing parabolic mirrors was possible. Hertz said that radio transmission between parabolic antennas was impractical. In 1892, Tesla delivered a speech before the Institution of Electrical Engineers of London in which he noted, among other things, that intelligence would be transmitted without wires. In 1893, he demonstrated wireless telegraphy (Bryant, 1988; Carl, 1966; Fagen, 1975; Maxwell, 1865; Salazar-Palma et al., 2011; Tarrant, 2001).

In the early 1860s, several people, including Bell, Gray, La Cour, Meucci, Reis, and Varley demonstrated telephones. In 1876, Alexander Bell patented the telephone (Fagen, 1975) in the United States. In 1880, Bell patented speech over a beam of light, calling this the *photophone*. This device was improved by the Boston laboratory of the American Bell Telephone Company and patented in 1897. E. J. P. Mercadier renamed the device the "radiophone," the first use of the term *radio* in the modern sense (Bryant, 1988; Carl, 1966; Fagen, 1975).

It is not often appreciated that before Marconi, several "wireless" approaches were attempted that did not involve radio waves. In the 1840s, Morse developed a method of sending messages across water channels or rivers without wires. He placed a pair of electrodes on opposite sides of a channel of water. As long as the electrodes on the same side of the water were spaced at least three times the distance across the water, practical telegraphic communication was possible. He demonstrated communication over a river a mile wide. In 1894, Rathenau extended Morse's concept to communicate with ships. Using a sensitive earpiece and a 150-Hz carrier current, he was able to communicate with ships 5 km from shore using electrodes 500 m apart. In 1896, Strecker extended the distance to 17 km (Sarkar et al., 2006).

In 1866, Loomis demonstrated the transmission of telegraph signals over a distance of 14 miles between two Blue Ridge Mountains using two kites with 590-ft lines. The two kite lines were conductors. He transmitted a small current through the atmosphere but used the Earth as the return path. This was somewhat like Morse's transmission through water (Sarkar et al., 2006).

In 1886, Edison devised an induction telegraph for communicating with moving trains. He induced the telegraphic signals onto the metal roof of the train by wires parallel to the train tracks. The grounded train wheels completed the circuit. While this system worked, it was not a commercial success (Sarkar et al., 2006).

In the 1880s, Hertz experimented with radio waves in the range 50–430 MHz. In 1894, Sir Oliver Lodge demonstrated a wireless transmitter and receiver to the Royal Society. In the early 1890s, Augusto Righi performed experiments at 1.5, 3, and 15 GHz. Soon several investigators including Marconi, Popov, Lebedew, and Pampa were performing wireless experiments at very high frequencies. In 1895, Bose used 10- to 60-GHz electromagnetic waves to ring a bell. About the same time, he made the first quantitative measurements above 30 GHz. In the 1920s, Czerny, Nichols, Tear, and Glagolewa-Arkadiewa were producing radio signals up to 3.7 THz. Very high frequency research of up to 300 GHz is currently underway. Commercial applications are currently being deployed as high as 90 GHz. High frequency microwaves in the 11–40 GHz range are finding applications in wide area networks and backhaul networks in urban areas. Higher frequency systems are being used for high density industrial campus and building applications (Bryant, 1988; Meinel, 1995; Wiltse, 1984).

In 1825, Munk discovered that a glass tube with metal plugs and containing loose zinc and silver filings tended to decrease electrical resistance when small electrical signals were applied. Using this principle to create a "coherer" detector, in 1890, Edouard Branly demonstrated the detection of radio waves at a distance. The coherer detector was improved by Lodge and others. Braun invented the galena crystal ("cat's whisker") diode in 1874 (Bryant, 1988). Crystal detectors were applied to radio receivers by Bose, Pickard, and others between 1894 and 1906 and were a big improvement over the coherer.

In 1894, Lodge detected "Hertzian" waves using Branly's coherer. In 1897, Tesla sensed electrical signals 30 miles away and received his basic radio patent. In 1898, Tesla demonstrated a radio controlled boat. In 1894, Marconi became interested in Hertzian waves after reading an article by Righi. After visiting the classes and laboratory of Professor Righi, Marconi began radio experiments in 1895. His radio receiver detector was the newly improved coherer. (Later he transitioned to Braun's crystal diode.) He created a wireless communications system that could ring a bell. Perhaps, he and Bose were the first to use radio for remote control. In 1896, he demonstrated a 1.75-mile 1.2-GHz radio telegraph system to the British Post Office. This was probably the first microwave radio link. In 1897, Marconi installed the first permanent wireless station on the Isle of Wight and communicated with ships. The next year he added a second station at Bournemouth. This was the first permanent point to point wireless link. In 1899, the link was used to send the first paid wireless digital transmission, a telegram. In 1899, Marconi sent messages across the English Channel, and in 1901, he sent signals across the Atlantic between St. Johns, Newfoundland and Poldhu, England. In 1897, Lodge patented a means of tuning wireless transmissions. In 1898, Braun introduced coupling circuits to obtain accurate frequency tuning and reduce interference between radio stations. Marconi and Braun were cowinners of the Nobel Physics Prize for their work (one of the few times the Nobel Prize was awarded to engineers rather than scientists) (Bryant, 1988; Tarrant, 2001).

The first audio transmission using radio was by the Canadian Reginald Fessenden in 1900. He also performed the first two-way transatlantic radio transmission in 1906 and the first radio broadcast of entertainment and music in the same year. However, commercial applications awaited the de Forest Audion. Early transmitters were broadband Hertzian types (spark gaps exciting tuned linear radiators). In 1906, the quenched spark transmitter was introduced by Wien. Continuous wave oscillations were introduced by Poulsen in 1906 (using an arc). Alexanderson, Goldschmidt, and von Arco quickly demonstrated continuous waves by other methods (Bryant, 1988).

On the basis of the comments by Crookes, in 1892, Hammond Hayes, head of the Boston laboratories of the American Bell Telephone Company, had John Stone and later G. Pickard investigate the possibility of radiotelephony using Hertzian waves. These investigations did not result in practical devices. Further investigation was delayed until 1914. By 1915, one-way transmissions of 250 and 900 miles had been achieved. Later that year speech was successfully transmitted from Arlington, Virginia, to Mare Island, California, Darien, Panama, Pearl Harbor, Hawaii, and Paris, France. In the 1920s, radio research in the Bell System was divided among the American Telephone and Telegraph (AT&T) Development and Research Departments and the Bell Laboratories, all in New York. The Bell Laboratories moved to New Jersey to be less troubled by radio noise and became the primary radio investigation arm of the Bell System. In the 1920s, terrestrial radio propagation was an art, not a science. In 1920, Englund and Friis of the Bell Labs began developing radio field strength measuring equipment. This was followed by field measurements to, as Friis stated, "demystify radio." By the early 1930s, an interest began to develop for long-distance relaying of telephone service by radio. It was clear that wide-frequency bandwidth was needed. The only spectrum available was above 30 MHz, the ultrashortwave frequencies (later termed *very high frequencies*, *ultrahigh frequencies*, and *superhigh frequencies*). Radio theory was developed and propagation experiments were carried out to validate it. By 1933, surface reflection, diffraction, refraction, and K factor (equivalent earth radius) were understood (Bullington, 1950; Burrows et al., 1935; England et al., 1933, 1938; Schelleng et al., 1933). By 1948, the theory and technology (Friis, 1948) had advanced to the point that fixed point to point microwave radio relay systems were practical (Bryant, 1988; Fagen, 1975; Friis, 1948).

At least three major technologies have been used for microwave antennas. In 1875, Soret introduced the optical Fresnel zone plate antenna. It was adapted to microwave frequencies in 1936 by Clavier and Darbord of Bell Labs (Wiltse, 1958). Dielectric and metal plate lenses were also tested (Silver, 1949, Chapter 11). However, by far, the most practical antenna was the reflector antenna. The first use of optical parabolic reflectors was by Archimedes during the siege of Syracuse (212–215 BCE). This reflector was used by Gregory (1663), Cassegrain (1672), and Newton (1672) to invent reflector telescopes. Hertz (1888) was the first to use a parabolic reflector at microwave radio frequencies. The World War II saw the widespread use of this type of antenna for radio detection and ranging (radar) systems. They remain the most important type of microwave antenna today (Rahmat-Samii and Densmore, 2009).

Radio transmission and reception antennas need to be above path obstructions. Convenient locations for the transmitter and receiver equipment are usually somewhere else. A transmission line that was free from reflecting or absorbing objects was needed to connect antennas and radio equipment. Coaxial cable was patented in Germany by Ernst Werner von Siemensin in 1884 and in the United States by Nikola Tesla in 1894. Hertz demonstrated the use of coaxial lines in 1887. Transmission by two parallel wire lines was demonstrated by Ernst Lecher in 1890. While this method had significantly less loss than coaxial cable, extraneous radiation made it impractical at microwave frequencies. Until the late 1930s, all radio transmission lines were two-conductor lines: two wire balanced line, one conductor (with implied ground plane mirror conductor), and coaxial cable. Two-conductor lines were popular for transmission at radio frequencies below 30 MHz (Bryant, 1984, 1988; Fagen, 1975; Millman, 1984).

Stripline- and microstrip-printed circuit technologies developed in the 1950s were used extensively in high frequency radio products. V. H. Rumsey, H. W. Jamieson, J. Ruze, and R. Barrett have been credited with the invention of the stripline. Microstrip was developed at the Federal Telecommunications Laboratories of ITT. Coaxial cable, while the most complex, tended to be the choice for most long-distance applications because of its low radiation and cross-talk characteristics. However, its relatively high loss was an issue for transmission of high frequency radio signals for long distances.

Coaxial cable was patented in England in 1880 by Oliver Heaviside and in Germany in 1884 by Siemens and Halske. The first modern coaxial cable was patented by Espenschied and Affel of Bell Telephone Laboratories in 1929. The first general-use coaxial connector was the UHF (ultrahigh frequency) connector created in the early 1940s. It was suitable for applications up to several hundred megahertz. The N connector, a connector for high frequency applications, was developed by Paul Neill at Bell Labs in 1944. This was followed by several derivative connectors such as the BNC (baby-type N connector) and the TNC (twist-type N connector). The N connector was limited in frequency to about 12 GHz, although precision versions were used up to 18 GHz. The SMA (SubMiniature connector version A) connector was adopted by the military in 1968 and became the industry standard for radio signals up to 18 GHz (precision versions are rated to 26 GHz). By extending the SMA design, the connectors 3.5 mm (rated to 34 GHz), 2.9 mm (or K) (rated to 46 GHz), 2.4 mm (rated to 50 GHz), 1.85 mm (rated to 60 GHz), and 1 mm (rated to 110 GHz) have been developed (Barrett, 1984; Bryant, 1984).

In 1887, Boys described the concept of guiding light through glass fibers. In 1897, Lord Rayleigh published solutions for Maxwell's equations, showing that transmission of electromagnetic waves through hollow conducting tubes or dielectric cylinders was feasible. R. H. Weber, in 1902, observed that the wave velocity of a radio signal in a tube was less than that in free space. He suggested that the wave was equivalent to a plane wave traveling in a zigzag path as it is reflected from the tube walls. DeBye, in 1910, developed the theory of optical waveguides. The first experimental evidence of radio frequency (RF) waveguides was demonstrated by George Southworth at the Yale University in 1920. The hollow waveguide was independently researched by W. Barrow of Massachusetts Institute of Technology (MIT) and George Southworth of Bell Laboratories in the mid-1930s. Southworth discovered the primary modes and characteristics of rectangular and circular waveguides. Southworth (1962) wrote a highly readable history of waveguide, waveguide filters, and related developments at Bell Labs. At nearly the same time, characteristics of various shapes of waveguides were also being developed by Brillouin, Schelkunoff, and Chu and also William Hansen began working on high Q microwave frequency resonant cavity circuits. Waveguide flanges of various types were invented to provide a cost-effective yet accurate way to attach waveguide components (Bryant, 1988; Fagen, 1975; Millman, 1984; O'Neill, 1985; Packard, 1984; Southworth, 1950).

During World War II, most of the critical waveguide and coax elements had been developed. Waveguide flanges (and flange adapters) provided cost-effective coupling of waveguide, directional couplers provided signal monitoring and sampling, filters provided frequency selectivity, and isolators and circulators provided two- and three-port directional routing of signals (Fig. 1.1) (Marcuvitz, 1951; Montgomery et al., 1948; Ragan, 1948; Southworth, 1950).

In 1897, Braun invented the Cathode Ray Tube with magnetic deflection. Fleming invented the two-electrode "thermionic valve" vacuum tube rectifier in 1904. de Forest improved on Fleming's rectifier by inventing the three-electrode "Audion" vacuum tube in 1906. In 1912, Colpitts invented the push–pull amplifier using the Audion. Meissner used the three-electrode (triode) tube to generate RF waves in 1913. About the same time, other oscillators were developed by Armstrong, de Forest, Meissner, Franklin, Round, Colpitts, and Hartley. Colpitts developed a modulator circuit in 1914. In 1918, Armstrong invented the superheterodyne receiver that is commonly used today. In 1919, Barkhausen and Kurz used a triode to generate radio frequencies as high as 10 GHz and Transradio, a subsidiary of Telefunken, introduced duplex radio transmission. Oscillators using coaxial line and waveguide (hollow cavities) were introduced in 1932 and 1935, respectively. Armstrong invented frequency modulation (FM) (Armstrong, 1936) in 1935. With the exception of a short period in the early 1970s [when single-sideband amplitude modulation

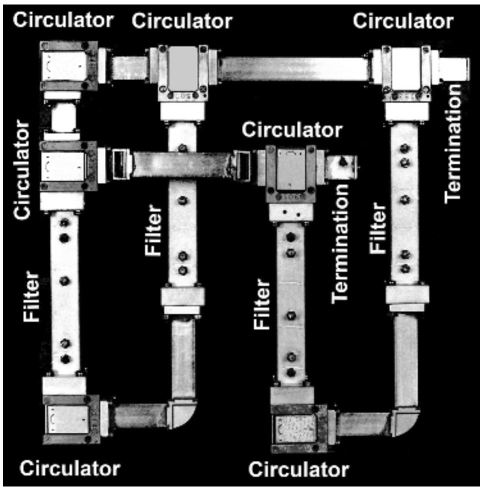

Figure 1.1 Waveguide coupling for multiple radios. *Source*: Reprinted with permission of Alcatel-Lucent USA, Inc.

(AM) was used briefly], FM was the primary modulation used in wideband microwave radios from the 1940s until the beginning of the digital radio era in the mid-1970s (Bryant, 1988; O'Neill, 1985).

Radar was the beginning of widespread applications of microwave radio frequencies. Radar was developed independently in the 1930s by Great Britain, Germany, Canada, Italy, Russia, Japan, the Netherlands, and the United States. In 1940, the United States formed the National Defense Research Committee (NDRC). Shortly thereafter, the NDRC's Microwave Committee began meeting at the private laboratories of Alfred Loomis. Microwave radar and navigation were the primary interests. At this time, the primary microwave research centers were at MIT and the Stanford University and the laboratories of Bell Laboratories, General Electric, Radio Corporation of America (RCA), and Westinghouse. In coordination with Sir Henry Tizard of the British Scientific Mission, the US government selected MIT as the contractor to carry out the radio research needed for the US and British military. This was organized as the Radiation Laboratory (Rad Lab). The 28-volume Radiation Laboratory Series of books detailing the results of the laboratory from 1940 to 1945 are beyond a doubt the most impressive single group of research reports on radio. Volumes 8, 9, 10, 12, and 13 (Kerr, 1951; Marcuvitz, 1951; Montgomery et al., 1948; Ragan, 1948; Silver, 1949) are still useful reading for microwave radio engineers. In roughly the same time period, low noise concepts such as noise figure and noise factor and low noise design concepts were discovered (Bryant, 1988; Fagen, 1975, 1978; Okwit, 1984; Sobol, 1984).

In 1937, Sigurd and Russell Varian demonstrated the first klystron oscillator. It was further developed by General Electric, the Stanford University, Sperry Gyroscope, and Varian Associates. Eventually, 3-GHz klystrons were manufactured by Bell Telephone Laboratories (Bell Labs), MIT Radiation Laboratories, Federal Telephone and Radio, General Electric, Westinghouse, Varian Associates, CSF in France, and the Alfred Loomis Laboratory in England. Klystrons have had a long use for low and medium power applications. However, their relatively low power conversion efficiency (30% conversion of DC power input to microwave power output) limited high power applications (Bryant, 1988; Fagen, 1975, 1978; Sobol, 1984).

A 200-MHz two-pole magnetron was first demonstrated by Albert Hull at General Electric in the 1920s. By 1930, both the Americans and the Japanese were using magnetrons to generate microwave signals. In 1935, a 3-GHz multiple cavity magnetron was developed by Hans Hollmann. In 1940, John Randall and Harry Boot produced a high power water-cooled magnetron and a 6-kW version was produced for the US government by GECRL of Wembley, England. During World War II, Percy Spencer, a Raytheon engineer, significantly improved magnetron efficiency and manufacturability. After the war, he invented the first microwave oven (Bryant, 1988; Fagen, 1975, 1978).

In 1942, Rudolf Kompfner invented the traveling wave tube, a medium power microwave amplifier. In 1947, Brattain, Bardeen, and Shockley at Bell Laboratories invented the point-contact transistor. In 1948, they invented the junction transistor. The first n–p–n transistor was demonstrated in 1950. Townes published the principle of the MASER (microwave amplification by stimulated emission of radiation) in 1951. In 1957, Esaki developed the germanium tunnel diode and Soulde described the LASER (light amplification by stimulated emission of radiation). In 1959, Jack Kilby of Texas Instruments and Robert Noyce of Fairchild independently developed the integrated circuit. The two shared the 2000 Nobel Prize in Physics for this achievement. In 1960, Khang and Atalla developed silicon–silicon dioxide field-induced surface devices [which led to metal–oxide–semiconductor field-effect transistors (MOS FETs)]. In 1961, Biard and Pittman of Texas Instruments invented gallium arsenide (GaAs) diodes. Today most microwave low and medium power applications use solid-state devices such as galium arsenide field-effect transistors (GaAs FETs). In 1962, Holonyak invented the first practical visible light-emitting diode (LED). In 1975, Ray Pengelly and James Turner invented the Monolithic Microwave Integrated Circuit (MMIC), although the concept had been mentioned in the early 1960s by Kilby. These devices were later further developed through support from the Defense Advanced Research Projects Agency (DARPA) (Bryant, 1988; Fagen, 1975, 1978; Millman, 1983).

In 1963, the Institute of Electrical and Electronic Engineers was formed by the merger of the Institute of Radio Engineers (IRE) and the American Institute of Electrical Engineers (AIEE) (Tarrant, 2001).

In 1909, Sommerfeld (1909) published his theoretical integral equation solution to free space radio wave propagation. This was the beginning of theoretical analysis of radio waves (Oliner, 1984). In the 1920s, Nyquist (1924, 1928) and Hartley (1928) published the first significant papers addressing information theory. In the 1920s, 1930s, and 1940s Kotel'nikov (1959), Nyquist, and Shannon developed the theoretical concepts of sampled signals and the relationship between the time and frequency domains. In 1939, Philip Smith, at Bell Telephone's Radio Research Lab in New Jersey, developed what is known as the *Smith chart* (Smits, 1985), a circular chart that shows the entire universe of complex impedances in one convenient circle. From the mid-1930s to the mid-1940s, considerable research was applied to (Norton, 1962). In 1944, 1945, and 1948, Rice (July 1944, 1948) published his mathematical analysis of random noise with and without a sine wave. In 1943, North (1963) defined what became called *Matched Filters* and Friis (1944) discovered the concept of noise figure. This work has been used extensively in the analysis of microwave fading statistics. In the late 1940s, Shannon (1948, 1949, 1950) and Tuller (1949) published significant papers on information theory of communications. In 1949, Weiner (1949) published his theory of linear filtering of signals in the presence of noise. About this same time he reported what has become known as the *Weiner–Hopf equation* that defines the relationship between signals in the time and frequency domains. In the 1950s, Cooley and Tukey developed the fast fourier transform (FFT) algorithm. Blackman and Tukey (1958) introduced the concept of signal power spectrum.

The Hamming (1950) and Reed–Muller (Muller, 1954; Reed, 1954) convolutional (Elias, 1955) and cyclic (Prange, 1957) codes were invented in the 1950s. Friis (1946) and Norton (1953) developed the modern radio wave transmission loss formula. In the 1950s, Bullington (1947, 1950, 1957, 1977) was developing the fundamental characteristics of practical microwave propagation. About the same time, Norton et al. (1955) were expanding Rice's work on the combination of constant and Rayleigh-distributed signals. In the 1950s and 1960s, Medhurst, Middleton, and Rice were developing the theory of analog FM microwave transmission. In 1960, Kalman (1960) published his theory of linear filtering of signal in the presence of noise and the Bose, Hocquenghem, Chaudhuri (BCH) (Bose and Ray-Chaudhuri, 1960; Hocquenghem, 1959), and Reed and Solomon (1960) coding were invented. In 1965, Wozencraft and Jacobs introduced the concept of geometric representation of signals. This is the basis of "constellations" now popular in modulation theory. In 1967, Viterbi (1967) published the algorithm currently used for most digital radio demodulators. Ungerboeck (1982) invented trellis coded modulation in 1982. In 1993, Berrou et al. (1993a) invented Turbo Coding. In 1996, Gallagher's (Gallagher, 1962) low density parity codes (LDPCs) were rediscovered by MacKay (Kizer, 1990; MacKay and Neal, 1996).

1.2 MICROWAVE TELECOMMUNICATIONS COMPANIES

Ericsson was started in 1876 as a telephone repair workshop in downtown Stockholm. It eventually became the primary supplier of telephones and switchboards to Sweden's first telecommunications operating company, Allmänna Telefonaktiebolag.

In 1897, Guglielmo Marconi formed the Wireless Telegraph and Signal Company (also known as the *Marconi Company Limited*, as well as the Wireless Telegraph Trading Signal Company). Marconi and his company created the first commercial radio transmission equipment and services. English Electric acquired the Marconi Company in 1946. The company was sold to the General Electric Corporation in 1987 and renamed the Marconi Electronic Systems. In 1999, most of the Marconi Electronic Systems assets was sold to British Aerospace (BAE) and it became part of BAE Systems. However, General Electric retained the Marconi name, Marconi Corporation, which it sold to Ericsson in 2006 (Bryant, 1988; Sobol, 1984).

Alcatel-Lucent was created in 2006 when Alcatel acquired Lucent Technologies. Alcatel was started in 1898 as Compagnie Générale d'Electricité. In 1991, it became Alcatel Alsthom. In 1998, it shortened its name to Alcatel. ALCATEL stands for "ALsacienne de Constructions Atomiques, de TELecommunications et d'Electronique" (Alsacian Company for Atomic, Telecommunication, and Electronic Construction). Over several years ITT, SEL, Thomson-CSF, Teletra, Network Transmission Systems Division (NTSD) of Rockwell International (including the former Collins Microwave Radio Division), Newbridge Networks, DSC Communications, Spatial Wireless, Xylan, Packet Engines, Assured Access, iMagicTV, TiMetra, and eDial. Lucent Technologies was formed in 1996 by AT&T when it spun off its manufacturing and research organizations (primarily Western Electric and Bell Labs). Lucent acquired Ascend Communications in 1999.

Alcatel-Lucent has three centers of microwave radio development and marketing: Velizy (southwest Paris), France; Vimercate (northeastern Milan), Italy (the former Teletra); and Plano (north Dallas), Texas (the former Collins Microwave Division of Rockwell International). The Alcatel-Lucent North American microwave radio facilities in Plano, Texas traces its roots to the Collins Radio Company, which was founded in 1933 by Arthur A. Collins in Cedar Rapids, Iowa. The Collins Radio Microwave Radio Division was founded in Richardson (north Dallas), Texas, in 1951. The first prototype of Collins commercial microwave equipment was placed in service between Dallas and Irving, Texas, in the spring of 1954. Later that year, the first Collins microwave radio system was sold to the California Interstate Telephone Company. By 1958, Collins was mass-producing microwave equipment and was providing the FAA (Federal Aviation Administration) with microwave systems providing communications and radar signal remoting networks. In 1973, Collins radio merged into Rockwell International. The Texas based Collins Microwave Radio Division ultimately became Rockwell's NTSD. During the 1970s, this division was the sole supplier of microwave radio equipment to the MCI (Microwave Communications, Inc.), with most of its other sales to the Bell operating companies. In 1976, NTSD introduced its first digital microwave radio, the MDR-11, an 11-GHz multiline system delivered to Wisconsin Bell (Madison to Eau Claire). In a parallel evolution, the Alcatel Network Systems' Raleigh, North Carolina, facility was originally operated by the ITT Corporation, which opened its first plant in 1958. From this facility, ITT first established its T1 spanline business in 1971, T3 fiber-optic transmission systems in 1979, and the first commercial single-mode fiber-optic transmission system in 1983. In 1987, ITT and Compagnie Generale d'Electricitie (CGE) of France agreed to a joint venture, creating Alcatel N.V.—the largest manufacturer of communications equipment in the world. Alcatel completed a buyout of ITT's 30% interest in the spring of 1992. The company was incorporated in the Netherlands, operated from Paris, and had its technical center in Belgium. This organization also created the Alcatel Network Systems Company, which was headquartered in Raleigh, North Carolina. In 1991, Alcatel purchased NTSD from Rockwell International and combined it with Alcatel Network Systems Company to form the Alcatel Network Systems, Inc., headquartered in Richardson, Texas. After the acquisition of DSC, the headquarters was moved to the former DCS facilities in Plano, Texas. In addition to microwave radios, this facility develops and markets fiber optics and digital cross-connect systems.

Founded in 1899 in Japan as the first US/Japanese joint venture with Western Electric Company, Nippon Electric (now NEC), headquartered in Tokyo, Japan, established itself as a technological leader early in its history by developing Japan's telephone communications system. Recognizing the impact information processing would eventually have on the world community, NEC was one of the earliest entrants into the computer and semiconductor markets in the early 1950s. NEC also supported much microwave research. NEC has also manufactured microwave radios since the early 1950s and introduced its first microwave radio product to the US market in the early 1970s. Later, NEC delivered its first digital microwave radio to the United States in the mid-1970s. The NEC Corporation of America's Radio Communications Systems Division (RCSD) is headquartered in Irving, Texas (Morita, 1960).

In 1903, the German wireless company Telefunken was formed. It was the first significant commercial wireless telegraph competitor to Marconi's company.

In 1878, Alexander Graham Bell and his financiers, Gardiner Hubbard and Thomas Sanders, created the Bell Telephone Company. The company name was changed to the National Bell Telephone Company in 1879 and to the American Bell Telephone Company in 1880. By 1881, the company bought a controlling interest in the Western Electric Company from Western Union. In 1880, the AT&T Long Lines was formed. This group became a separate company named the *American Telephone and Telegraph Company* in 1885. In 1899, the AT&T Company bought the assets of American Bell and became the Bell System. In 1918, the federal government nationalized the entire telecommunications industry, with national security as the stated intent. In 1925, AT&T created Bell Telephone Laboratories ("Bell Labs"). In 1956, the Hush-A-Phone v. United States ruling allowed a third-party device to be attached to rented telephones owned by AT&T. This was followed by the 1968 Carterfone Decision that allowed third-party equipment to be connected to the AT&T telephone network. On January 8, 1982, the 1974 United States Department of Justice antitrust suit against AT&T was settled. Under the settlement AT&T ("Ma Bell") agreed to divest its local exchange service operating companies in return for a chance to go into the computer business. Effective January 1, 1984, AT&T's local operations were split into seven independent Regional Bell Operating Companies (RBOCs), or "Baby Bells." Western Electric was fully absorbed into AT&T as AT&T Technologies. After its own attempt to penetrate the computer marketplace failed, in 1991, AT&T absorbed the NCR (National Cash Register) Corporation. After deregulation of the US telecommunications industry via the Telecommunications Act of 1996, NCR was divested again. At the same time, the majority of AT&T Technologies and Bell Labs was spun off as Lucent Technologies. In 1994, AT&T purchased the largest cellular carrier, McCaw Cellular. In 1999, AT&T purchased IBM's Global Network business, which became AT&T Global Network Services. In 2001, AT&T spun off AT&T Wireless Services, AT&T Broadband, and Liberty Media. AT&T Broadband was acquired by Comcast in 2002. AT&T Wireless merged with Cingular Wireless in 2004 to become Cingular; in 2007, it became AT&T Mobility. In 2005, SBC Communications acquired AT&T Corp. and became AT&T Inc.

General Telephone & Electronics (GTE), founded in Wisconsin in 1918, was started as the Richland Center Telephone Company. It changed names many times: Commonwealth Telephone Company (1920), Associated Telephone Company (1926), General Telephone Corporation (1935), and finally, GTE Corporation (1959, when it merged with Sylvania Electric Products). In 1964, the Western Utilities Corporation merged with GTE. In 1955, GTE acquired Automatic Electric, the largest independent manufacturer of automatic telephone switches. In 1959, it acquired Lenkurt Electric Company, Inc., a manufacturer of microwave radio and analog multiplex equipment. Lenkurt Electric was established in 1933 as a wire-line telephone multiplex manufacturer. It moved from San Francisco to San Carlos in 1947. Its radio product line was terminated in 1982 and a number of employees migrated to Harris Farinon. At the same time, the company adopted the name GTE Corporation and formed GTE Mobilnet Incorporated to handle the company's entrance into the new cellular telephone business. In 1983, Automatic Electric and Lenkurt were combined as GTE Network Systems. GTE became the third largest long-distance telephone company in 1983 through the acquisition of Southern Pacific Communications Company. At the same time, Southern Pacific Satellite Company was also acquired, and the two firms were renamed GTE Sprint Communications Corporation and GTE Spacenet Corporation, respectively. Through an agreement with the Department of Justice, GTE conceded to keep Sprint Communications separate from its other telephone companies and limit other GTE telephone subsidiaries in certain markets. In 1997, Bell Atlantic merged with NYNEX but retained the Bell Atlantic name. In 2000, Bell Atlantic merged with GTE and adopted the name Verizon. In 2005, Verizon acquired MCI (formerly WorldCom).

The company that eventually became IBM was incorporated in the state of New York on June 16, 1911, as the Computing-Tabulating-Recording (C-T-R) Company. On February 14, 1924, C-T-R's name was formally changed to International Business Machines Corporation. In 1944, IBM and Harvard introduced the Mark 1 Automatic Sequence Controlled Calculator based on electromechanical switches. In 1952, IBM introduced the 701, a computer based on the vacuum tube. The 701 executed 17,000 instructions per second and was used primarily for government and research work. The IBM 7090, one of the first fully transistorized mainframes, could perform 229,000 calculations per second. In 1964, IBM introduced the System/360, the first large "family" of computers to use interchangeable software and peripheral equipment.

Farinon Electric was established in San Carlos, California, in 1958. Seeing a need for a high quality, light-route radio for telecommunications, Bill Farinon left his job with Lenkurt Electric to begin business in a Redwood City cabinet shop. Farinon Electric was started as a limited partnership with $140,000, of which $90,000 was cash (Farinon and his wife came up with $30,000, Farinon's father invested $20,000, and a friend invested $40,000.). With two employees, he started designing and building the first Farinon Electric PT radio offering 36 channels at 450 MHz for the telephone and industrial market. In 1980, Farinon Corporation was sold to Harris Corporation and became known as *Harris Farinon*. In 1998, the division was renamed the Harris Microwave Communications Division. Meanwhile, elsewhere in California, in 1984, Michael Friedenbach, Robert Friess, and William Gibson formed the Digital Microwave Corporation (DMC) to serve the short-haul microwave market. In 1998, DMC acquired MAS Technology and Innova Corporation. In 1999, the company name was changed to Stratex Networks. Plessey Broadband was acquired in 2002. In 2007, Stratex Networks and the Microwave Communications Division of Harris Corporation were merged to create Harris Stratex Networks. This independent company was majority-owned by Harris Corporation. In 2010, Harris spun off the company as Aviat Networks.

In 1899, Cleyson Brown formed the Brown Telephone Company in Abilene, Kansas. The company's name was changed to United Utilities in 1938 and to United Telecommunications ("United Telecom") in 1972. In 1980, United Telecom introduced a nationwide X.25 data service, Uninet.

The Southern Pacific Railroad operated its telephone system as an independent company, called the *Southern Pacific Communications Corporation* (*SPCC*). In the late 1950s, this primarily wire-based communications system began transitioning into a microwave radio relay network. In 1983, the GTE Corporation, parent company of General Telephone, purchased the network and renamed it GTE Sprint Communications. In 1986, Sprint was merged with US Telecom, the long-distance arm of United Telecom, to form the US Sprint. This partnership was jointly owned by GTE and United Telecom. Between 1989 and 1991, United Telecom purchased controlling interest in US Sprint. In 1991, United Telecom changed its name to Sprint. In the mid-1980s, Sprint began building a nationwide fiber-optics network. In 1986, a highly successful "dropping pin" ad was used to describe the superiority (clear sound depicted by the pin's "ting" when it hit a hard surface) of the "all-fiber" digital network. In 1988, Sprint ran an ad showing a microwave radio tower being blown up, thereby emphasizing their claim of an "all-fiber" network (in an effort to differentiate the Sprint network from the largely microwave based AT&T and MCI networks). While this marketing approach was very successful, it did not win friends within the microwave community (who were quick to point out that radio was more reliable than multiline fiber—a problem later solved with ring architecture). Some microwave "old timers" are happy to point out that Sprint rebuilt the microwave tower and now has many fixed point to point microwave links in their all-digital network.

1.3 PRACTICAL APPLICATIONS

In the early 1860s, several people, including Bell, Gray, La Cour, Meucci, Reis, and Varley demonstrated telephones (transmitters and receivers). In 1876, Alexander Bell and Thomas Watson, as well as Elisha Gray, demonstrated the first practical telephones. Both Bell and Gray filed patent documents the same day in 1886. Meucci sued Bell for patent infringement but died in 1889 before the suit could be completed. Western Union, in conjunction with Edison and Gray's company, Gray and Barton, began offering telephone service and entered into litigation with Bell concerning patent rights. Edison had invented a superior carbon telephone transmitter but Bell had the better receiver. About the same time, Western Union formed the Western Electric Manufacturing Company. In 1878, the New England Telephone Company was formed. The same year the Bell Telephone Company was formed by Bell and his financiers. The next year the two companies merged to form the National Bell Telephone Company. In 1880, Bell's company became the American Bell Telephone Company. In 1882, the company bought controlling interest in Western Electric Company from Western Union. About the same time, Western Union and Bell settled their long-standing patent infringement conflict. The same year AT&T was formed to create a nationwide long-distance telephone network. This organization eventually became AT&T Long Lines. In 1899, AT&T purchased the assets of the American Bell Telephone Company and added local service to its long-distance services. In 1925, AT&T created Bell Telephone Laboratories. In the United

States, much of the radio development was conducted by Bell Labs. These laboratories were funded from federally regulated telephone service income. After much legal maneuvering, the US Department of Justice imposed the Consent Decree of 1956 on AT&T. Bell Labs was treated as a national resource. The results of its employees were viewed as national property. Until this decree was changed in 1984, AT&T could not receive royalties for any of its inventions (such as the transistor and laser) (Bryant, 1988; IEEE Communications Society, 2002; O'Neill, 1985; Schindler, 1982; AT&T Bell Laboratories, 1983; Thompson, 2000).

The first commercial telephone exchange was opened in New Haven, Connecticut, in January 1878. In 1889, the first coin-operated telephone was installed in a bank in Hartford, Connecticut. In 1892, the Strowger Automatic Telephone Exchange Company (later Automatic Electric Company) installed the first automatic telephone exchange, the Stroger Step by Step. Later other automatic mechanical switches were invented and installed: the Panel in 1930 and the Crossbar in 1938. The cost of mechanical switch upgrades was increasing with each generation. In the 1950s, the concept of a software-defined switch was envisioned as a way to reduce the cost of upgrades and changes to telephone switches. Electronic switches were trialed in the 1960s. The first digital switching toll office system in North America was the Western Electric 4ESS introduced in 1972. Initially, these switches had analog telephone interfaces. Later they evolved to strictly digital DS1 interfaces. The digitization of the national telecommunications transportation network followed the evolution of the 4ESS. Northern Telecom introduced the first local office switch, the DMS10, in the late 1970s followed by Western Electric's 5ESS in early 1989 (Schindler, 1982; Thompson, 2000).

With the proliferation of telephone service, the need for telephone lines increased dramatically. A solution to this problem was the development of frequency division multiplex (FDM) systems that "stacked" multiple telephone channels into one composite wide bandwidth analog signal. At first they connected cities via coaxial cable. Later analog FM microwave radios were used to transport the FDM signals (Fig. 1.2).

The use of these telecommunication systems was universal. Compared to long-distance cable systems, the microwave radio systems were relatively inexpensive and could be placed practically anywhere (Fig. 1.3). Many companies evolved worldwide to supply this telecommunication equipment.

In 1916, ship to shore two-way radio communication was demonstrated between the USS New Hampshire and Virginia based transmitter and receiver locations. Bell Labs developed the CW-936 500-kHz to 1.5-MHz radio telephones for the Navy. About 2000 of these radiotelephones were installed on US and British ships during the World War I. Western Electric produced the 600-kHz to 1.5-MHz SCR-68 ground to air radiotelephones for the US Navy (Bryant, 1988; Fagen, 1978).

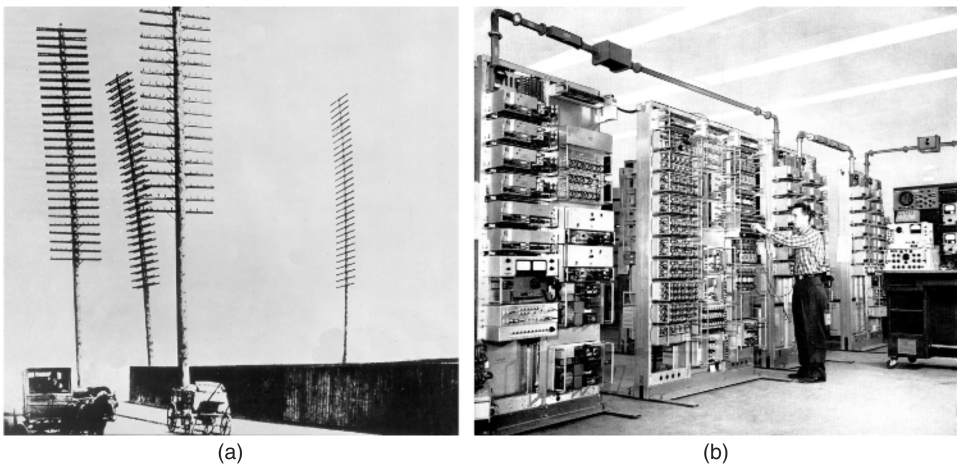

Figure 1.2 (a, b) Too many telephone lines and the early FDM-FM microwave radio system solution. *Source*: Photos from Collins Microwave Radio Company archives. Reprinted with permission of Alcatel-Lucent USA, Inc.

(a) (b)

Figure 1.3 (a, b) Microwave radio locations. *Source*: Photos from archives of Collins Microwave Radio Division of Rockwell International. Reprinted with permission of Alcatel-Lucent USA, Inc.

About the same time, commercial applications began. Long-distance telephone service was needed on the Catalina Island off the coast of California. However, due to wartime shortages, a cable system could not be provided. Radio was a logical choice. The project was started in April 20, 1920, and engaged in service on July 16, 77 days later. Rapid deployment has been a standard radio system feature ever since. Transatlantic telephony experiments were conducted in the 1920s. Radio telephone service between the United States and England began on January 7, 1927. The cost for a 3-min call was $75. By 1939, shortwave radio telephone service was available between most major cities in the world (Fagen, 1978; Sobol, 1984).

Although Guarini had suggested radio relay communications in 1899, this was not attempted for several years. In 1925, the RCA installed an experimental radio link across the English Channel. The first commercial radio telephone service was initiated in 1927 between Great Britain and the United States. In 1931, French and English engineers of Les Laboratoires Standard (later Laboratoire Central de Telecommunication) and Standard Telephone and Cables (later International Telephone and Telegraph), under the direction of Andre Clavier, experimented with a 40-km microwave radio link across the English Channel (one telephone/telegraph channel between Calais and St. Margarets Bay). It operated with a 1-W 1.7-GHz transmitter with 10-ft (3-m) parabolic antennas. Reports on this project (Armstrong, 1936) first used the terms *micro waves* (two words). The first commercial microwave radio link was installed between the Vatican and the Italian PTT (Post, Telephone and Telegraph) in 1932. In 1933, a link was installed between Lympne, England, and St. Inglevert, France, which was in continuous operation until 1940. Also, in 1933, at the Chicago World's Fair, Westinghouse demonstrated 3.3-GHz radio links using parabolic antennas. Two of these systems were sold to the US Army Signal Corps for $2500 each. In 1936, the British General Post Office opened a multichannel link between Scotland and Northern Ireland. This 65-km link operated at 65 MHz using AM to carry nine voice channels. In Germany, Lorenz and Telefunken produced a single-channel 500-MHz AM system for the Army in 1937. In 1939, a 1.3-GHz FM 10-channel magnetron-based system was introduced in Stuttgart. These German systems were deployed widely in Europe and North Africa. These networks covered 50,000 route km, with terminals as far apart as 5000 km (Carl, 1966; Fagen, 1978; Sobol, 1984).

The first microwave radio relay system radios were the British Wireless Set No. 10 developed by the UK Signals Research and Development Establishment (SRDE). The Pye Company built the RF section and the TMC Company built the multiplex. It was an eight-telephone-channel TDM pulse width modulation 5-GHz radio system designed to operate in tandem as a radio relay. It was demonstrated to the US Signal Corps Labs and Bell Laboratories on September 1942. This spurred the development of similar systems in the United States: the RCA AN/TRC-5 and the Bell Labs AN/TRC-6 (Carl, 1966; Fagen, 1978; Sobol, 1984).

In 1941, Bell Laboratories tested a 12 voice channel AM system between Cape Charles and Norfolk. In 1943, Western Union installed the first intercity commercial microwave radio system using the RCA microwave equipment. In 1945, AT&T Corporation was operating a multichannel FM system between New York and Philadelphia. In 1948, Western Union had a 1000-mile 24-hop microwave radio system connecting New York, Washington, DC, and Pittsburgh. This was the first system to use unattended radio repeater locations and was the first use of loop topology to increase system reliability. A 7-hop (tandem radio path) 100 voice channel 4-GHz system between New York and Boston (300 km) was introduced in 1947. This experimental system, named *TD-X*, was the basis of the widely deployed improved system, named *TD-2*, which provided 489 telephone channels or one television channel per radio channel. In 1951, AT&T completed the TD-2 107-hop, 12 RF channel per hop, system between New York and San Francisco. This system spanned 4800 km and reached 12,000 km of total hop length. The short-haul 11-GHz TJ system was announced in 1957. In 1955, AT&T began the development of the 1800 voice channel 6-GHz TH system. By 1960, it had been deployed in parallel with the TD-2 system (Fagen, 1978; Friis, 1948; Sobol, 1984; Thayer et al., 1949).

In 1954, the US Air Force SAGE system employed the first (1200-baud analog telephone channel) modems to communicate between computer systems. In the 1960s, digital cable systems began to be deployed worldwide to interconnect telephone operating company switches. In France, TDM using PCM had been studied beginning in 1932. These techniques were used extensively in the United States beginning in 1962 with T1 digital cable spans with 24 voice channel banks connecting the 4ESS tandem switches. The transport was digital but the connections to the 4ESS were analog. Later direct DS1 interfaces were added to the switch. The introduction of the electronic 4ESS switch in 1976 spurred the development of terrestrial digital systems. In Europe, 30 voice channel TDM/PCM E1 links were being deployed (Fagen, 1978; Sobol, 1984; Welch, 1984).

In 1971, Hoff at Intel invented the silicon microprocessor that is used in personal computers. Jobs and Wozniak created the Apple I computer in 1976. The 16-bit microprocessor computer was introduced in 1980 by IBM using the Microsoft disk operating system (MS-DOS) developed by Gates and Allen. Jobs and Wozniak introduced the Macintosh computer in 1984.

Before 1949, the Federal Communications Commission (FCC) assigned microwave spectrum only to telecommunications common carriers. After that date, it began to license private microwave systems on a case by case basis if no common carrier service was available.

In 1959, the FCC, in its “Above 890” ruling, decided to allow licensing private intercity microwave systems for voice or data service at frequencies above 890 MHz. After that ruling, in the United States, microwave frequencies were defined as starting at 890 MHz. This definition is still in common use in the United States today. In 1962, the first telecommunication satellite, Telstar, was placed into orbit. In 1963, the American Standard Code for Information Exchange (ASCII) was defined. In 1968, DARPA began deployment of ARPANET (Advanced Research Projects Agency Network) and placed it in service in 1971. This was the first step in creating the Internet. This was to have a profound impact on telecommunications worldwide. In the United States, the 1968 Carterfone Decision created the opportunity to interconnection of customer-owned telephone equipment. In 1969, the first digital radio relay system went into operation in Japan. It operated at 2 GHz with a transmission capacity of 17 Mb/s. The FCC’s Specialized Common Carrier Decision of 1969 decreed that new microwave companies could compete with the existing regulated telephone companies to sell private network transmission services. This brought a flood of Specialized Common Carriers utilizing microwave radio. In 1968, Western Microwave merged with Community Television cable system and became American Tele-Communications, with Western Tele-Communications (WTCI) and Community Tele-Communications (CTCI) subsidiaries. The same year the parent company’s name was changed to Tele-Communications Inc. (TCI) and the headquarters was moved to Denver, Colorado. WTCI used the 1969 ruling to begin building an extensive microwave network used primarily for video distribution. By 1974, WTCI had become a large US microwave common carrier, second only to AT&T. MCI was founded as Microwave Communications, Inc. on October 3, 1963. Initially it built microwave relay stations between Chicago and St. Louis. In 1969, the umbrella company Microwave Communications of America, Inc. (MICOM) was incorporated and MCI began building its national private long-distance microwave radio network. MCI was purchased by Verizon in 2006. In 1979, the Times Mirror Company entered the cable network business. Not long after that the company formed Times-Mirror Microwave Communications Company of Austin, Texas. This company operated a large microwave network that provided, on a long-term contractual basis, transmission capacity to Telcos (long-distance resellers, independent telephone companies, and regional Bell companies) to carry their voice calls.

In 1970, Data Transmission Co. (DATRAN) filed for FCC approval of a nationwide system exclusively for data transmission over digital microwave radios. The DATRAN system was a nationwide all-digital-switched microwave radio network, which linked subscriber terminals in 35 metropolitan areas. The same year Norman Abramson and Franklin Kuo at the University of Hawaii introduced ALOHANET, the first large-scale deployment of data packets over radio. In 1986, this concept was refined by Robert Metcalfe at Xerox PARC into Ethernet, the technology that led to the IEEE 802.3 Local Area Network data interface standard. The 1972 FCC "Open Skies" ruling created domestic satellite communications carriers. These systems shared the terrestrial microwave radio 4- and 6-GHz common carrier bands. The same year Southern Pacific Communication (the forerunner of Sprint) got the FCC approval for an 11-state common carrier microwave radio network. In 1977, Bell Labs installed the first Advanced Mobile Phone System (AMPS). This was the first cellular radio system. The need for transmission circuits between cell sites would eventually expand the use of microwave radio systems. In the late 1970s, AT&T digitized its network enabling it to carry data traffic. In 1983, Judge Greene approved divestiture of AT&T. The AT&T divestiture (the US Department of Justice's Modified Final Judgment of the 1956 Consent Decree), effective January 1, 1984, separated AT&T from seven new RBOCs (Ginsberg, 1981).

1.4 THE BEAT GOES ON

In the late 1940s, all fixed point to point microwave relay systems used analog FM transmission. It carried video and telephony exclusively. FDM was used to aggregate the 4-kHz-wide analog telephone channels for transmission over FM radios.

In the 1970s, single-sideband analog radios were used to increase the analog transmission capacity. However, by the late 1970s, digital transmission began to be deployed worldwide. TDM was used to aggregate the PCM analog telephone channels. Various standards were developed in different countries to multiplex various levels of TDMed digital signals ("asynchronous" systems in North America and Plesiochronous Digital Hierarchy in Europe) (Gallagher, 1962; AT&T Bell Laboratories, 1983).

In 1988, Bellcore's Synchronous Optical Network (SONET) and in 1989, the ITU-T's Synchronous Digital Hierarchy (SDH) were finalized, setting new standards for worldwide digital transport interconnectivity. The SONET and SDH systems were widely deployed in radio networks in the 1990s.

Beginning in the 1970s, while data equipment was being developed, data network architectures were beginning to become standardized. The IBM Systems Network Architecture (SNA) introduced the concept of layered hierarchical peer processes. Its six-layer architecture was very popular. The Digital Equipment Corporation (DEC) also provided a five-layer Digital Network Architecture (DNA). The International Standards Organization (ISO) defined a seven-layer Reference Model [Open Systems Interconnection (OSI) "seven-layer stack"]. ARPANET developed its four-layer architecture that has become the standard for the Internet. There were many other architectures that achieved various levels of popularity. However, today the Internet ("Ethernet and IP") architecture is by far the most popular (Green, 1984; IEEE Communications Society, 2002; Konangi and Dhas, 1983).

J. C. R. Licklider, in his January 1960 paper, Man-Computer Symbiosis, proposed "a network of such [computers], connected to one another by wide-band communication lines [which provide] the functions of present-day libraries together with anticipated advances in information storage and retrieval and symbiotic functions." During the 1960s, Paul Baran and Donald Davies independently proposed data networks based on the principle of breaking down all digital messages into message blocks called *packets*. AT&T engineers and management discounted the concept as unworkable. Unlike the AT&T approach of circuit-switching networks, the proposed packet networks would store and forward message blocks over different routes based on various criteria. With adequate path redundancy, these networks were inherently highly reliable in the face of localized network outages. Leonard Kleinrock, in 1961, was the first to develop a mathematical theory of this technology (Hafner and Lyon, 1996).

In 1962, Licklider was appointed head of the US Department of DARPA. Licklider created a computer science community associated with DARPA. In 1964, Ivan Sutherland took over as head of DARPA. Sutherland recruited Robert Taylor, from Dallas, Texas, to manage the DARPA computer networks. Taylor's office had three different communications terminals to three different computers at three different locations. The complexity of interacting with each computer and the inability to transfer information from one computer to another prompted Taylor to propose a data network to connect all facilities performing research for DARPA using a common interface. Taylor proposed this network and the project was approved for implementation (Hafner and Lyon, 1996).

Taylor's network began as a network of four nodes connecting the University of California, Los Angeles (UCLA), Stanford Research Institute, University of Utah, and University of California, Santa Barbara. The nodes were controlled by Interface Message Processors (IMPs), the forerunner of the modern router. The IMPs and the network concept were specified and managed by Bolt Beranek and Newman (BBN), and the IMPs were designed and manufactured by Honeywell. The data connections among the nodes were data modems connected to audio circuits leased from AT&T. The IMP packet switches and their connections were called the *ARPANET*. The UCLA Network Measurement Center would deliberately stress the network to highlight bugs and degradations. The IMPs reported various quality metrics and statistics to a central Network Control Center (NCC) to facilitate effective management of network transmission quality. The NCC was also the focal point for coordinated software upgrade of all IMPs via remote download; the concept of a data Network Operations Center (NOC) was introduced. Request for Comments Number 1 (RFC 1), entitled "Host Software," was written by Steve Crocker in 1969. About the same time, an informal group, which was eventually called the *Network Working Group* (*NWG*), was formed to oversee the evolution of the network. This group eventually became the Internet Engineering Task Force (Fial, R., private communication, 2010, Hafner and Lyon, 1996).

The first electronic mail (e-mail) between two machines was sent in 1971 by Ray Tomlinson at BBN. Tomlinson chose the @ symbol as the separator between the user name and the user's computer. In 1972, Robert Metcalfe and others at Xerox PARC adapted the packet techniques from ALOHANET (Norman Abramson and others) to create a coaxial cable network connecting Alto computers. Metcalfe first called the new network *Alto Aloha* and later *Ethernet*. In the early 1970s, AT&T was asked if it wanted to take over ARPANET. AT&T and Bell Labs studied the proposal but declined. About the same time, ITU developed a packet network standard X.25. In 1974, Vint Cerf and Robert Kahn described the end to end routing of packets called *datagrams*, which encapsulated digital messages. The paper also introduced the concept of gateways. In 1975, Yogen Dalal, using the Cerf and Kahn concepts, developed a specification for transmission control protocol (TCP). The original concept of TCP included both packet protocol and packet routing. In a TCP review meeting in 1978, Vint Cerf, Jon Postel, and Dan Cohen decided to split the packet protocol and routing functions of TCP into two separate functions: Internet protocol (IP) and TCP. All ARPANET host computers were converted to Transmission Control Program and Internetwork Protocol (TCP/IP) operation in 1983 (Fial, R., private communication, 2010, Hafner and Lyon, 1996).

Also in 1993, Mosaic, the first graphical Internet browser, was released by Marc Andreessen and Eric Bina at the National Center for Supercomputing Applications (NCSA) at the University of Illinois Urbana-Champaign. The next year the Netscape Navigator appeared, which quickly expanded the Web's presence and made it a viable commercial medium. In 1988, the ISO produced the OSI protocol standard. It was intended to replace TCP/IP. Its complexity and insistence to replace (rather than supplement) existing standards made its adoption and implementation very difficult. In 1991, Tim Berners-Lee of CERN published a summary of the World Wide Web. For the first time the Internet was introduced to the concepts of HyperText Transfer Protocol (HTTP), HyperText Markup Language (HTML), the Web browser, and the Web server. HTML is the markup language used for documents served up by a Web server. HTTP is the transfer protocol developed for easy transmission of these hypertext documents by the Web server. A Web browser consumed these documents and drew them on a page. While these sat upon the already existing infrastructure of the Internet, they were one of the several formats at the time used for sharing information. Some of the other formats popular at the time were Gopher and FTP. The HTML format was a little more user friendly, embedding navigation and display together, but it was not until the graphical browser was created that it became the de facto standard. In 1995, the US government formally turned over operation of the Internet to private Internet service providers (ISPs). The world would never be the same (Kizer, M., private communication, 2010, Hafner and Lyon, 1996).

The new millennium has shown a significant increase in adoption of IP technology for interconnecting all forms of digital transmission. For now, the SONET and SDH systems are maintaining a hold on the long-distance transmission market. However, the user community drop and edge connections are rapidly transitioning to IP. IP, with its evolving Quality of Service features, is the new wave of digital transmission. Fixed point to point microwave network evolution mirrors that transition.

REFERENCES

Armstrong, E., "A Method of Reducing Disturbances in Radio Signaling by a System of Frequency Modulation," *Proceedings of the IRE*, pp. 689–740, May 1936.

AT&T Bell Laboratories, *Engineering and Operations in the Bell System*, *Second Edition*. Murray Hill: AT&T Bell Laboratories, 1983.

Barrett, R. M., "Microwave Printed Circuits—The Early Years," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 32, pp. 983–990, September 1984.

Bennett, W. R. and Davey, J. R., *Data Transmission*. New York: McGraw-Hill, 1965.

Berrou, C., Glavieux, A. and Thitimajshima, P., "Near Shannon Limit Error-Correcting Coding and Decoding: Turbo Codes," *IEEE International Conference on Communications Proceedings*, pp. 1064–1070, 1993.

Blackman, R. B. and Tukey, J. W., *The Measurement of Power Spectra from the Point of View of Communications Engineering*. New York: Dover Publications, 1958.

Bose, R. and Ray-Chaudhuri, D., "On a Class of Error-Correcting Codes," *Information and Control*, Vol. 3, pp. 68–79, 1960.

Bryant, J. H., "Coaxial Transmission Lines, related Two-Conductor Transmission Lines, Connectors and Components: A U. S. Historical Perspective," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 32, pp. 970–983, September 1984.

Bryant, J. H., "The First Century of Microwaves—1886 to 1986," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 36, pp. 830–858, May 1988.

Bullington, K., "Radio Propagation at Frequencies Above 30 Megacycles," *Proceedings of the IRE—Waves and Electrons Section*, pp. 1122–1136, October 1947.

Bullington, K., "Radio Propagation Variations at VHF and UHF," *Proceedings of the IRE*, pp. 27–32, January 1950.

Bullington, K., "Radio Propagation Fundamentals," *Bell System Technical Journal*, Vol. 36, pp. 593–626, May 1957.

Bullington, K., "Radio Propagation for Vehicular Communications," *IEEE Transactions on Vehicular Technology*, Vol. 26, pp. 295–308, November 1977.

Burrows, C. R., "Propagation Over Spherical Earth," *Bell System Technical Journal*, Vol. 14, pp. 477–488, July 1935.

Burrows, C. R., Hunt, L. E. and Decino, A., "Ultra-Short Wave Propagation: Mobile Urban Transmission Characteristics," *Bell System Technical Journal*, Vol. 14, pp. 253–272, April 1935.

Carl, J., *Radio Relay Systems*. London: MacDonald, 1966.

Elias, P., "Coding for Noisy Channels," *IRE Convention Record*, Vol. 3, pp. 37–47, 1955.

England, C. R., Crawford, A. B. and Mumford, W. W., "Some Results of a Study of Ultra-Short-Wave Transmission Phenomena," *Bell System Technical Journal*, Vol. 12, pp. 197–227, April 1933.

England, C. R., Crawford, A. B. and Mumford, W. W., "Ultra-Short-Wave Transmission and Atmospheric Irregularities," *Bell System Technical Journal*, Vol. 17, pp. 489–519, October 1938.

Fagen, M. D., *A History of Engineering & Science in the Bell System, The Early Years (1875-1925)*. Murray Hill: Bell Telephone Laboratories, 1975.

Fagen, M. D., Editor, *A History of Engineering and Science in the Bell System, National Service in War and Peace (1925–1975)*. Murray Hill: Bell Telephone Laboratories, 1978.

Friis, H. T., "Noise Figures of Radio Receivers," *Proceedings of the IRE*, pp. 419–422, July 1944.

Friis, H. T., "A Note on a Simple Transmission Formula," *Proceedings of the IRE—Waves and Electrons Section*, pp. 254–256, May 1946.

Friis, H. T., "Microwave Repeater Research," *Bell System Technical Journal*, Vol. 27, pp. 183–246, 1948.

Gallagher, R. G., "Low Density Parity Check Codes," *IRE Transactions on Information Theory*, Vol. 8, pp. 21–28, January 1962.

Ginsberg, W., "Communications in the 80's: The Regulatory Context," *IEEE Communications Magazine*, Vol. 19, pp. 56–59, September 1981.

Green, P. E., Jr., "Computer Communications: Milestones and Prophecies," *IEEE Communications Magazine*, Vol. 22, pp. 49–63, May 1984.

Hafner, K. and Lyon, M., *Where Wizards Stay Up Late, the Origins of the Internet*. New York: Simon & Schuster, 1996.

Hamming, R., "Error Detecting and Error Correcting Codes," *Bell System Technical Journal*, Vol. 29, pp. 41–56, January 1950.

Hartley, R., "Transmission of Information," *Bell System Technical Journal*, Vol. 7, pp. 535–563, July 1928.

Hocquenghem, A., "Codes Correcteurs d'Erreurs," *Chiffres*, Vol. 2, pp. 147–156, 1959.

IEEE Communications Society, *A Brief History of Communications*. Piscataway: IEEE, 2002.

Kalman, R. E., "A New Approach to Linear Filtering and Prediction Problems," *Transactions of the ASME*, Vol. 82, pp. 35–45, January 1960.

Kerr, D., *Propagation of Short Radio Waves*, *Radiation Laboratory Series*, Volume 13. New York: McGraw-Hill, 1951.

Kizer, G. M., *Microwave Communication*. Ames: Iowa State University Press, 1990.

Konangi, V. and Dhas, C. R., "An Introduction to Network Architectures," *IEEE Communications Magazine*, Vol. 21, pp. 44–50, October 1983.

Kotel'nikov, V. A., *The Theory of Optimum Noise Immunity*. New York: McGraw-Hill, 1959.

MacKay, D. J. C. and Neal, R. M., "Near Shannon Limit Performance of Low Density Parity Check Codes," *Electronics Letters*, Vol. 32, pp. 1645–1655, August 1996.

Marcuvitz, N., *Waveguide Handbook*, *Radiation Laboratory Series*, Volume 10. New York: McGraw-Hill, 1951.

Maxwell, J. C., "A Dynamical Theory of the Electromagnetic Field," *Philosophical Transactions of the Royal Society of London*, Vol. 155, pp. 459–512, 1865.

Meinel, H. H., "Commercial Applications of Millimeterwaves History, Present Status and Future Trends," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 43, pp. 1639–1653, July 1995.

Millman, S., Editor, *A History of Engineering and Science in the Bell System, Physical Sciences (1925–1980)*. Murray Hill: AT&T Bell Laboratories, 1983.

Millman, S., Editor, *A History of Engineering and Science in the Bell System, Communications Sciences (1925–1980)*. Indianapolis: AT&T Technologies, 1984.

Montgomery, C. G., Dicke, R. H. and Purcell, E. M., Editors, *Principles of Microwave Circuits*, *Radiation Laboratory Series*, Volume 8. New York: McGraw-Hill, 1948.

Morita, K., "Report of Advanced in Microwave Theory and Techniques in Japan - 1959," *IRE Transactions on Microwave Theory and Techniques*, Vol. 8, pp. 395–397, July 1960.

Muller, D., "Application of Boolean Switching Algebra to Switching Circuit Design," *IEEE Transactions on Computers*, Vol. 3, pp. 6–12, September 1954.

North, D. O., "An Analysis of the Factors which Determine Signal/Noise Discrimination in Pulse-Carrier Systems," *Proceedings of the IEEE*, pp. 1016–1027, July 1963.

Norton, K. A., "Transmission Loss in Radio Propagation," *Proceedings of the IRE*, pp. 146–152, January 1953.

Norton, K. A., "Radio-Wave Propagation During World War II," *Proceedings of the IRE*, pp. 698–704, May 1962.

Norton, K. A., Vogler, L. E., Mansfield, W. V. and Short, P. J., "The Probability Distribution of the Amplitude of a Constant Vector Plus a Rayleigh-Distributed Vector," *Proceedings of the IRE*, pp. 1354–1361, October 1955.

Nyquist, H., "Certain Factors Affecting Telegraph Speed," *Bell System Technical Journal*, Vol. 3, pp. 324–346, April 1924.

Nyquist, H., “Certain Topics in Telegraph Transmission Theory,” *AIEE Transactions*, Vol. 47, pp. 617–644, April 1928.

O’Neill, E. F., *A History of Engineering & Science in the Bell System, Transmission Technology (1925–1975)*. Murray Hill: AT&T Bell Laboratories, 1985.

Okwit, S., “An Historical View of the Evolution of Low-Noise Concepts and Techniques,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 32, pp. 1068–1082, September 1984.

Oliner, A. A., “Historical Perspectives on Microwave Field Theory,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 32, pp. 1022–1045, September 1984.

Packard, K. S., “The Origin of Waveguides: A Case of Multiple Rediscovery,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 32, pp. 961–969, September 1984.

Prange, E., “Cyclic Error-Correcting Codes in Two Symbols,” *Air Force Cambridge Research Center Technical Report TN-57-103*. Cambridge: United States Air Force, 1957.

Ragan, G., Editor, *Microwave Transmission Circuits*, *Radiation Laboratory Series*, Volume 9. New York: McGraw-Hill, 1948.

Rahmat-Samii, Y. and Densmore, A., “A History of Reflector Antenna Development: Past, Present and Future,” *SBMO/IEEE MTT-S International Microwave & Optoelectronics Conference*, pp. 17–23, November 2009.

Reed, I., “A Class of Multiple-Error-Correcting Codes and a Decoding Scheme,” *IEEE Transactions on Information Theory*, Vol. 4, pp. 38–49, September 1954.

Reed, I. and Solomon, G., “Polynomial Codes Over Certain Finite Fields,” *Journal of the Society of Industrial Applied Mathematics*, Vol. 8, pp. 300–304 1960.

Rice, S. O., “Mathematical Analysis of Random Noise,” *Bell System Technical Journal*, Vol. 23, pp. 282–332, July 1944, and Vol. 24, pp. 46–156, January 1945.

Rice, S. O., “Statistical Properties of a Sine Wave Plus Random Noise,” *Bell System Technical Journal*, Vol. 27, pp. 109–157, January 1948.

Salazar-Palma, M., Garcia-Lamperez, A., Sarkar, T. K. and Sengupta, D. L., “The Father of Radio: A Brief Chronology of the Origin and Development of Wireless Communications,” *IEEE Antennas and Propagation Magazine*, Vol. 53, pp. 83–114, December 2011.

Sarkar, T. K., Mailloux, R. J., Oliner, A. A., Salazar-Palma, M. and Sengupta, D. L., *History of Wireless*. Hoboken: John Wiley & Sons, Inc., 2006.

Schelleng, J. C., Burrows, C. R. and Ferrell, E. B., “Ultra-Short Wave Propagation,” *Bell System Technical Journal*, Vol. 12, pp. 125–161, April 1933.

Schindler, G. E., Jr., Editor, *A History of Engineering and Science in the Bell System, Switching Technology (1925–1975)*. Murray Hill: AT&T Bell Laboratories, 1982.

Shannon, C. E., “A mathematical theory of communication,” *Bell System Technical Journal*, Vol. 27, pp. 379–423, 623–656, July and October 1948.

Shannon, C. E., “Communication in the Presence of Noise,” *Proceedings of the IRE*, pp. 10–21, January 1949.

Shannon, C. E., “Recent Development in Communication Theory,” *Electronics*, Vol. 21, pp. 80–83, April 1950.

Silver, S., Editor, *Microwave Antenna Theory and Design*, *Radiation Laboratory Series*, Volume 12. New York: McGraw-Hill, 1949.

Smits, F. M., Editor, *A History of Engineering and Science in the Bell System, Electronics Technology (1925–1975)*. Indianapolis: AT&T Technologies, 1985.

Sobol, H., “Microwave Communications—An Historical Perspective,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 32, pp. 1170–1181, September 1984.

Sommerfeld, A., “Über die Ausbreitung der Wellen in der drahtlosen Telegraphie,” *Annals of Physics*, Vol. 28, pp. 665–736, 1909.

Southworth, G. C., *Principles and Applications of Waveguide Transmission*. New York: Van Nostrand, 1950.

Southworth, G. C., *Forty Years of Radio Research*. New York: Gordon and Breach, 1962.

Tarrant, D. R. *Marconi's Miracle*. St. John's: Flanker Press, 2001.

Thayer, G. N., Roetken, A. A., Friis, R. W. and Durkee, A. L., "A Broad-Band Microwave Relay system Between New York and Boston," *Proceedings of the IRE—Waves and Electrons Section*, pp. 183–188, February 1949.

Thompson, R. A., *Telephone Switching Systems*. Boston: Artech House, 2000.

Tuller, W. G., "Theoretical Limits of the Rate of Transmission of Information," *Proceedings of the IRE*, pp. 468–478, May 1949.

Ungerboeck, G., "Channel Coding with Multilevel/Phase Signals," *IEEE Transactions on Information Theory*, Vol. 28, pp. 55–67, January 1982.

Viterbi, A. J., "Error Bounds for Convolutional Codes and an Asymptotically Optimum Decoding Algorithm," *IEEE Transactions on Information Theory*, Vol. 13, pp. 260–269, April 1967.

Weiner, N., *Extrapolation, Interpolation and Smoothing of Stationary Time Series with Engineering Applications*. Cambridge: The MIT Press, 1949.

Welch, H., "Applications of Digital Modulation Techniques to Microwave Radio Systems," *Proceedings of the IEEE International Conference on Communications*, Vol. 1, June 1978, pp. 1170–1181, September 1984.

Wiltse, J. C., "History of Millimeter and Submillimeter Waves," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 32, pp. 1118–1127, September 1984.

Wiltse, J. C., "History and Evolution of Fresnel Zone Plate Antennas for Microwaves and Millimeter Waves," *Antennas and Propagation Society International Symposium*, Proceedings, Vol. 2, pp. 722–725, July 1999.