contracts on radar beacons and related equipment. From 1955 to 1963, he was a system engineer with the RCA Missile and Surface Radar Department in Moorestown, NJ, working on the AN/UPS-1, AN/FPS-16, AN/FPS-49, and related radars. In 1958 he was the first recipient of RCA's David W. Sarnoff Award for outstanding achievement in engineering, and in 1961 he received the M. Barry Carlton Award of the IRE Professional Group on Military Electronics. Since 1963, he has been with the Raytheon Company as a consulting scientist specializing in radar systems. His work there has covered detection and measurement capabilities of conventional and phased-array radars, as applied to defense and navigational systems. He performed early system studies for the Missile Site Radar of the Safeguard system, and generated the original designs for the AN/TPN-19 Precision Approach Radar, the dual-frequency Hostile Weapons Locator radar, and specialized low-altitude surveillance radars for Navy use. He has published some 70 papers on radar in the professional journals. His first book, *Radar System Analysis*, (Englewood Cliffs, NJ: Prentice-Hall, Inc.), appeared in 1964, and he has collaborated with H. R. Ward in the *Handbook of Radar Measurement*, also published by Prentice-Hall in 1969. He is general editor of the Artech Radar Library, and has compiled and edited a seven-volume series of reprints on radar subjects. He also contributed to *Modern Radar* (New York: Wiley, 1965) and to the *Electronics Engineers' Handbook* (New York: McGraw-Hill, 1975), as well as lecturing to special courses at University of Pennsylvania and The George Washington University. From 1972 to 1975 he was Chairman of the Radar Systems Committee of the AES Society.

Microwave Communications—An Historical Perspective

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Abstract—**The history of microwave communications includes major discoveries of Morse, Maxwell, Hertz, Marconi, and other pioneers of the radio and electronics fields. This paper traces the early work which led to wireless communications and the long struggle to achieve practical microwave radio. Even though the first microwave line-of-sight systems were demonstrated and placed in service during the 1930's, it was not until the late 1940's and early 1950's that large transcontinental microwave transmission systems were implemented. The 1960's and 1970's witnessed significant progress in the technology and application of line-of-sight microwave communication systems. Other microwave systems including troposcatter, satellite, and millimeter waveguide transmission systems were also developed during the 1960's and 1970's. The past 100 years have witnessed very significant breakthroughs in radio technology, particularly at microwave frequencies, that have had an enormous impact on the world's societies through improved communications for the populace, business, and governments.**

I. Introduction

LONG-DISTANCE communication, both on the earth and over vast regions of space, is one of the major triumphs of microwave technology. The contributions of microwave communication to society have exceeded the greatest hopes of the early pioneers of radio science. Communication has been one of the major drivers in the development and advancement of microwave technology over the past 100 years, and, in fact, led to other applications including radar and radio astronomy.

The history of microwave communication over the past century includes some of the major advances and applications of science and technology. This paper will briefly summarize the early discoveries of the radio and communication arts, the efforts to increase the operating frequency of radio, the first microwave communication links, and the explosive growth of the technology following World War II. Satellite systems, millimeter waveguide communication, and modern microwave radio will also be discussed.

The author apologizes at the outset for omitting discussion on some of the major contributions that have been made in the field, but, in a paper a few pages long, it is only possible to recognize a few of the many major accomplishments that have led to microwave communications as exist today.

It is assumed that most readers are quite familiar with, or have easy access to, literature on the progress in the field during the past 10 to 15 years. The recent advances will be briefly mentioned, but the emphasis of the paper will be on the earlier work that foreshadowed the developments of the 1970's and 1980's.

II. Early History

It is necessary in a study of the history of microwave communications to start with the monumental discoveries and demonstrations in the fields of electrical communication, and the application of the principles of electromagnetic wave propagation to radio.

The first demonstration of electrical communication over a substantial distance was by Samuel F. B. Morse in 1844, with a dot-dash message over a single wire between Baltimore and Washington, DC, using the earth as a return path. Primitive systems and concepts were shown earlier by the Russian, Schilling, and the Germans, Gauss and Weber, but Morse's invention led to the establishment of telegraphy as a viable communication media. The initial installa-

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tions of telegraph systems over land routes were followed by the first transatlantic telegraph cable in 1858.

Alexander Graham Bell, in 1876, demonstrated that the human voice could be electrically transmitted over wire and was granted a patent [1] for the telephone in 1876, although the patent was the subject of lengthy disputes, involving counter claims by the American, Elisha Gray; Italians, Antonio Meucci and Innocenzi; and others. Bell started the first telephone company in 1878 in New Haven, CT. The expansion of this small system to the giant ATT was a remarkable achievement with no parallel in history. It is ironic that the 100th anniversary year of IEEE coincides with the year of divestiture of ATT.

The growth of the telephone and telegraph networks in the late 1800's covered the major cities with a vast maze of wires and poles. While long-distance telegraphy was possible, telephone was not. Clearly, an alternative to wire communications was required.

During the period of the initial growth of telephone and telegraph systems, work that would lead to wireless communication was starting. Englishman James Clark Maxwell's theoretical work in 1864 hypothesized that light was an electromagnetic (EM) phenomena, and that EM energy propagated as waves in space. In Germany, Heinrich Hertz experimentally proved Maxwell's theories in 1888, and consequently established the basis for wireless communication. It was a paradox, however, that Hertz did not appreciate the potential impact on communications of EM wave propagation in space. When queried about the application of the waves to telegraphy, Hertz responded [2],

> However the vibrations of a transformator or telegraph are far too slow; take for example a thousand in a second, which is a high figure, then the wavelength in the ether would be 300 km and the focal length of the mirror must be the same magnitude. If you could construct a mirror as large as a continent, you might succeed with such experiments, but it is impractical to do anything with ordinary mirrors, as there would not be the least effect observable.

Obviously, Hertz envisioned the transmission of telegraphic symbols directly at the data rate, since modulated carrier systems were not known at that time. Fortunately, others did pursue the application of EM waves in space to communications, which eventually led to radio transmission.

Hertz's work was performed at an extremely high frequency [3]. A spark gap was used to produce oscillations with each arc discharge of about 100 MHz, which were radiated in free space. He placed a reflector some distance from the oscillator and thus generated standing waves. Using a loop with a spark gap as a detector, he was able to detect the E-field peaks of the standing wave at distances of about 25 ft from the oscillator. He was then able to calculate that the waves were propagating at the speed of light and, indeed, confirmed Maxwell's theory. It is significant that Hertz used parabolic surfaces to direct EM waves during his experiments—truly a forerunner of the parabolic reflectors used extensively today.

The Englishman, Oliver Lodge, in 1894 improved the sensitivity of Hertz's loop detector [4] by coupling the spark gap loop to a "Coherer," invented in 1892, by another Englishman, Edward Branly. The coherer consisted of a glass tube filled with metallic filings. The resistance of a current path through the filings decreased under the influence of a spark or discharge. A trembler was used to periodically shake the filings back to the original high-resistance state. A relay was used to magnify current and drive an inker which would register or record the received signal. In 1898, Lodge also patented the concept of a tuned transmitter and receiver, one of the most famous and important patents in radio history.

The Russian, A. S. Popov [5], further improved the sensitivity of Lodge's coherer detection scheme in 1895 by using choking coils and a long vertical wire antenna connected to earth through the coherer.

The above advances caught the attention of a young Italian, who was to become the prime mover for the technology of radio and to win a Nobel Prize (1909) for these efforts.

III. Development of Radio

Guglielmo Marconi [6], in 1894, at the young age of 20, first read about Hertz's experiments and started work to develop wireless communications. He made significant improvements in the original spark gap transmitter and the Lodge coherer and, by 1896, was transmitting Morse Code messages over a distance of two miles. Marconi moved to England in 1897 and established the British Marconi Company that year, and an American subsidiary two years later. In 1901, Marconi demonstrated transatlantic transmission of telegraphy over a 1700-mi path from England to Newfoundland.

Marconi's early experiments on radio, during 1894–1896, were at frequencies on the order of 1000 MHz [7], although his major efforts in developing commercial wireless service were at very much lower frequencies in order to achieve practical long-distance communications. In fact, years later he reminisced that the progress on long-wavelength radio was so rapid and comparatively easy that all attention was distracted from short waves for a long period. Other factors, to be discussed later in this paper, also frustrated the development of microwave radio.

The reasons for improved long-distance propagation at low frequencies were not fully understood at the start of the twentieth century. Many scientists believed that radio waves would propagate over the earth's surface just as light waves, and transmission beyond the line-of-sight could only be achieved by diffraction. Marconi disproved this theory for low frequencies and was able to achieve huge distances for transmission. As Marconi moved towards the lower frequencies, he had to abandon the directive parabolic antennas he used in the 1-GHz range and, instead, used long wire antennas in the form of an inverted L. Practical frequencies used for commercial service were in the range of tens of kilohertz. An understanding of the physics of propagation in the atmosphere was gained through the work of the Englishman, Heaviside, and others in the early 1900's. Their major discoveries were the effects of ionized layers on propagation of EM waves.

The early spark gap transmitters and detectors left much to be desired for reliable transmission of telegraphy and were not well suited to telephony, although the American, Reginald Fessenden [8] did succeed in transmitting speech over a one-mi path using a spark gap transmitter in 1900. Consequently, a search began for reliable continuous-wave sources of EM waves. Nikola Tesla [9], in the United States, first conceived the idea of using high-frequency rotary machine alternators during the 1890's, but was unsuccessful in applying the technique to radio. Fessenden was successful in 1906 [10] with an 80-KHz alternator built by the General Electric Company. Several years followed before Ernest Alexanderson of GE built alternators capable of transatlantic transmission; however, earlier units were applied in ship-to-shore systems. Fessenden was also responsible for inventing the heterodyne receiver as an attempt to improve radio receivers, but it was many years before this approach received practical implementation.

One of the major inventions of all time, the vacuum tube, provided significant new possibilities for radio [11]. Thomas Edison, in 1883, first noted the emission of electrons from heated filaments. J. Ambrose Fleming used this effect in his diode detector patented in 1904, and Lee DeForest invented the triode vacuum tube for the control of a flow of electrons in 1907. Rapid progress followed in the development and application of vacuum tubes, first as receiving devices, and then as sources of EM energy for transmitters. The vacuum tube was, of course, instrumental in the development of high-frequency and, ultimately, microwave radio.

Other important developments [12] in the United States in the radio during this period included the crystal detector invented by H. H. Dunwoody and G. W. Pickard, in 1906, and the regenerative circuit (feedback) invented by DeForest and Armstrong in 1913.

The new technologies of the early 1900's opened the door to reliable radio communication for voice and telegraphy messages. Long wavelengths were used for long-distance communications and shorter wavelengths were used for short paths, and also for ship-to-shore communications, since the smaller antenna structures were better suited for mounting on ships. Manufacturing techniques for production quantities of tubes developed quickly.

The alternator was the primary source used in high-power transmitters, but significant progress was made in applying tube technology for high power. In 1914 [13], ATT constructed a 170-KHz transmitter using parallel banks of tubes, each capable of producing several watts of undistorted power. Eighteen such tubes were used in 1915 to establish a telephone link from Montauk Point, NY, to Wilmington, DE, a distance of 200 mi. Later that same year, the distance was extended to St. Simon Island, GA, a distance of 800 mi. The radio links were incorporated in the Bell System wire-line networks, and practical long-haul telephony using radio links and wire lines were demonstrated.

Experiments to apply the same type of transmitters to transoceanic distance were also conducted by ATT in 1914. The number of tubes was increased to 500 to produce 2.5 KW of power. Communication was established over paths as long as 4900 mi in tests between Montauk Point and Paris, Panama, and San Diego.

During this very fruitful period, significant improvements were made in the application of tubes in circuits such as modulators, oscillators, and amplifiers. Also, new modulation schemes including Armstrong's FM system were invented and applied.

IV. High-Frequency Radio

Wavelengths of 200 to 10 000 m seemed adequate for the initial radio work. However, some effort was directed towards higher frequencies again, since the hope of communication with highly directive antennas was very attractive. As described above, early researchers used spark gaps to achieve radiation at phenomenally high frequencies, yet the challenge to be met before high-frequency radio could be achieved was how to use vacuum tubes.

The General Electric Company, in 1917, produced a 250-W air-cooled triode called a Pilotron. W. C. White of GE described circuits with coils and capacitors that could extend the Pilotron operating range to tens of megahertz. G. Southworth [14], in 1919, then at Yale University, replaced the coils and capacitors described by White with transmission lines (Lecher lines), reduced the capacitance effects by removing the base of the tube, and was able to operate the tube at wavelengths between 110 and 200 cm. Southworth called this frequency band Ultra Radio Frequencies. He conducted propagation measurements in this band and set up very primitive radio links. He also started a series of experiments using propagation in troughs filled with water, which were to become the basis of his famous waveguide work in later years.

During the early 1920's, Marconi returned to experimentation with higher frequency radio [15]. The band between 3 and 20 MHz was explored on 100–300-mi paths between Holland and England. Although some problems, due to atmospheric conditions, were encountered, the usefulness of the frequency bands 3–20 MHz (HF) for long-distance communication was established. The economy of the new band, which used relatively low transmitter power, appeared to be considerably better than the very high-power kilohertz bands.

Even though the HF band received the majority of Marconi's attention during the years 1919–1924, he also conducted research at much higher frequencies. Since little or no test equipment, sources, and components were available, he, as well as other researchers studying this new band, had to develop their own equipment and tools.

The primary power source investigated by Marconi was the electron oscillator, invented by Barkhausen and Kurz in 1919. By applying a negative potential to the plate and a large positive voltage to the grid, electrons were made to oscillate in position between the grid and plate. Oscillations above 300 MHz were easily obtained. Marconi made considerable advances in the use of this tube. He used a balanced push–pull configuration with the plate-grid and grid-filament circuits tuned by Lecher lines, similar to what Southworth used on the Pilotron tube. Frequency modulation was achieved by applying the modulating signal to the plate. Significant power and reasonable life at that time (500 h) were achieved.

Marconi also developed a regenerative receiver for 600-MHz operation. Balanced low-power electron oscillators were used as the radio frequency detector, which was then followed by a two-stage audio amplifier. The transmitter and receiver could be mounted on the back of parabolic reflectors. The feeds for the reflectors were initially open Lecher lines and were eventually replaced with coaxial feeders.

Marconi conducted radio tests of the system in 1931, in Italy, and was able to establish good quality speech over an 18-mi path between Santa Margherita and Levante. During the spring of 1932, an improved version of the radio with the capability for duplex operation and operation with 2-wire subscriber systems was demonstrated. In the summer of 1932, propagation tests from Santa Margherita to the yacht, Elettra, clearly demonstrated that 600-MHz signals could be received well beyond the optical line-of-sight, much to the chagrin of certain investigators who theorized that microwaves could not be transmitted beyond the horizon. An additional experiment, using a receiver at an elevation of 1,000 ft at Cape Figari and a transmitter in Sardinia, produced good speech quality over a 168-mi path.

V. The First Microwave Radios

Based on the success of the 1931–32 experiments, Vatican authorities [16] approached Marconi to install a 57-cm microwave link between Vatican City and the summer residence of the Pope at Castel Gandolfo, a path of 15 mi. The system was to have both a telephone and a teleprinter capability. The installation was completed, and service was inaugurated by Pope Pius XI in February of 1933.

Work in France during this same period was aimed at achieving communications at even higher frequencies. A. G. Clavier [17]–[19] and a team of ITT engineers at Les Laboratories, Le Materiel Telephonique, in Paris, developed an 18-cm wavelength microwave radio that was demonstrated in March 1931 on a duplex telephone path between Dover, England and Calais, France. The system, called the Micro-Ray radio, produced high-quality communication.

The source of microwave energy for the Micro-Ray radio was an improved Barkhausen tube. The filament which served as the cathode was surrounded by a helicoidal grid structure, which was in turn surrounded by a cylindrical plate which served as the electron reflecting surface. Electrodes connecting to the grid structure protruded through the envelope of the tube and were connected to the transmission line tuners. The oscillator was amplitude modulated by applying the modulation to both the reflecting plate and grid to maintain a constant frequency and achieve at least 40-percent AM. The receiver was of the regenerative type and used a similar Barkhausen tube for demodulation. The demodulated signal was filtered and fed to audio amplifiers.

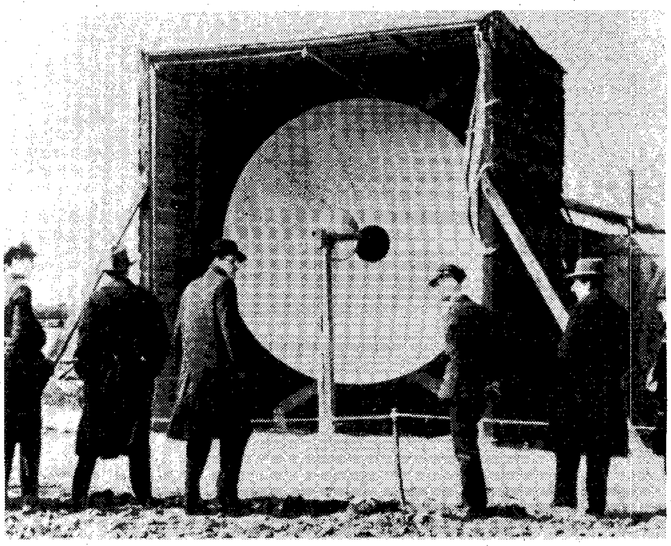


Fig. 1. Terminal of Micro-Ray link, 1931 (Courtesy of ITT).

The demonstration system delivered 1/2 W of microwave power at 18-cm wavelength to an antenna with a ten-ft-diam parabolic reflector. A photograph of one terminal of the system is shown in Fig. 1.

Based on the successful demonstration of the radio in 1931, a contract was awarded to build a system for service between the airports at Lympne, France, and St. Inglevert, England. Duplex telephony and teleprinter channels were provided. The link was 56 km long and was placed in service early in 1934.

Clavier carried on his work to perfect microwave communication and to study propagation effects, some of which were noted on the Lympne–St. Inglevert path. In 1941, he was the first to make measurements of beyond-the-horizon propagation of microwaves with wavelengths of the order of 20 cm or less. This was done secretly in Occupied France during World War II, under the eyes of the Germans, from a fishing trawler that traveled to sea conveniently along the path of a microwave beam from a transmitter mounted in the attic of a house on a seaside cliff [20].

Efforts on microwave communication research in the United States during the 1930's were centered at Bell Laboratories (BTL) on radio as well as waveguide transmission systems. The choice of an optimum frequency band for radio relay was a topic of major interest at BTL in the early 1930's [21]. Selections ranged from 100 MHz where substantial power could be generated, to 500 MHz where Barkhausen oscillators would provide far less power, greater bandwidth, and have higher directivity. A 500-MHz path was set up between the New York Telephone Company in Manhattan and New Jersey Bell in Newark, a distance of eight and one-half mi. The transmitter was frequency modulated, and moderate-gain zone-plate antennas were utilized. It was evident to the researchers that a microwave amplifier was needed for practical radio relay, particularly with tubes that could operate at frequencies considerably higher than 500 MHz.

An effort to extend the frequency range of standard triodes was undertaken at BTL by A. L. Samuel in 1934. Triodes with extremely close electrode spacing were designed for operation with Lecher lines. Successful operation was achieved at 20-cm wavelength in 1936. Tubes operating as a second harmonic oscillator produced about 1 W at 3 GHz.

A very important breakthrough in the technology of microwave tubes occurred in 1935 in Germany when Heil and Heil published their historic paper [22] in which they discussed the velocity modulation of electrons in a short gap, and the consequent bunching as the electrons traverse a drift tube. The output is obtained as the bunch passes through a short output gap. In the United States in 1939, the Varian brothers [23] used the velocity modulation principle to invent the klystron, both amplifiers and oscillators. The reflex klystron oscillator was similar to the Barkhausen oscillator discussed previously. Thus, finally the transit time limitations in conventional tube devices were overcome. The klystron incorporated cavities as an integral part of the tube and the early problems of coupling tubes and external resonant circuit elements were removed. By mid-1939, A. L. Samuel [24] and his BTL team built a klystron suited for waveguide use and achieved 15-dB gain over a 5-MHz bandwidth at 3 GHz, with an output power of 1 W.

As a result of demonstrations of microwave radio in Europe and the United States, and the success in achieving amplification at microwave frequencies, a planning activity was initiated at BTL to design and build a 3-GHz [25] microwave link. The radio was on the drawing board in 1941, but the work was halted due to the start of World War II, and the shift of effort to support development of systems for the government.

Also, during the early 1930's, Southworth at BTL rejuvenated his earlier work at Yale on waveguides [26]. The efforts were directed towards investigations of the technology for long-haul microwave communications in waveguides. Southworth's initial efforts at Yale and at Bell were conducted at fairly low frequencies. Therefore, in order to keep the size of the waveguides reasonable, dielectric loading was used by filling the guides with water. In 1932, when the high-frequency French Barkhausen tubes discussed above became available, tests at frequencies up to 2 GHz were possible, and air-filled guides were used. The various modes of propagation in metal pipes were studied and measured. The theory of waveguide propagation was studied by S. Schelkunoff at BTL. An outstanding finding, discovered theoretically and substantiated experimentally, was identification of the TE_{01} mode in circular waveguide. This mode exhibited a loss characteristic that decreased with frequency. This TE_{01} mode was to play a key role in the efforts to develop a waveguide transmission system in the future.

In May of 1933, a 20-ft-long waveguide was built and used to demonstrate transmission of telegraph signals. The first message was "Send money," symbolic of the depression at that time. An 875-ft-long waveguide line was built at Netcong, NJ, in 1933, and used for transmission at 17.5 cm. This line was used for some of the first studies on waveguide discontinuities and led the way to studies of irises, tuning sections, and waveguide sections as circuit elements.

Southworth's efforts were expanded in 1934, and a laboratory was set up in Holmdel, NJ. Instruments for measurements were refined and invented. Waveguide benches, standing-wave detectors, wavemeters, high-Q cavities, crystal detectors, filters, multiplexers, and other components were developed and numerous papers were written. In 1938, a demonstration of waveguide transmission was given at the IRE Convention in New York City. Work was extended to 3-cm studies, but, in 1940, emphasis was changed to support development of systems for the U.S. defense effort, as the war had already begun in Europe.

VI. Microwave Communication During World War II

Enormous strides in the development of microwave technology were made during World War II, with the bulk of the effort aimed at radar systems. Southworth's waveguide group at Bell Labs [27] became heavily involved in this effort and invented many waveguide components for radar, including waveguide lobe switches, rotary joints, improved filters, waveguide modulators and demodulators, phasing devices, waveguide hybrids including the magic-tee, directional couplers, attenuators, power measuring devices, and other instruments. While these components were extremely useful for the radar work, they were also applicable for communication systems. Work was also performed in the 3–0.6-cm bands for radar applications.

As mentioned earlier, work on the 3-GHz radio relay for the Bell System was interrupted at the beginning of World War II; however, in 1943, the U.S. Army approached ATT to develop a microwave radio system. A similar system was under development by the British, and early models were successfully used by them in the North African campaign. The first prototypes of the U.S. Army radio, the AN/TRC-6, were completed at the end of 1943, and production started shortly after.

The AN/TRC-6 [28] was a pulse-position modulation system that provided eight duplex voice channels through time division multiplexing and operated at 4.5 GHz. This radio, which was radically different than any previous microwave radio, was one of the first to have multichannel capability. The system was truck transportable and could be erected in a few hours. The microwave equipment either was placed atop a 50-ft tower with five-ft-diam parabolic reflector antennas, or, in a second version, utilized the microwave equipment at ground level with a parabolic reflector, also at ground level, that beamed the energy towards a 48° plane reflector located at the top of the tower.

Peak pulsed powers of a few watts were obtained by pulsing a reflex klystron with one-μs pulses. A four-μs pulse was used as the synchronizing signal. It is very likely that this form of modulation was a direct carry-over from the successful use of pulse modulation in radar. The radio had a superheterodyne receiver, one of the first applications of this approach in microwave radio. The receiver down converter utilized a silicon crystal detector and a reflex klystron local oscillator with automatic frequency control, and produced a 58.5-MHz IF signal. The IF amplifier had AGC to maintain constant-amplitude output pulses despite fading. Versions of the radio with one or two antennas were available. In the single-antenna case, a diplexer using waveguide filters separated transmitted and received signals.

Each voice circuit was sampled according to the Nyquist Sampling Theorem at 8 KHz, and the one-μs pulse position was determined by signal amplitude at the time of sampling. A pulse framing structure was used to multiplex eight voice circuits into a single-pulse train. The eight message circuits were high-quality telephone circuits and met commercial standards for long-distance telephone transmission. Individual circuits were either two- or four-wire and could be used for signaling, dialing, facsimile, and multichannel voice-frequency telegraphy. A single-voice circuit could handle 18 teletypewriter facilities. Both terminal and repeater versions of the radio were provided for multihop repeater service.

Two-way voice transmission over AN/TRC-6 links totaling 1600 mi, and one-way transmission over 3200 mi were demonstrated. In addition to use in the field, test hops of the radio were established to study microwave propagation over extended periods. Idiosyncrasies of microwave transmission were observed. The static which haunted Marconi in the 10–30-MHz band did not exist, but often on quiet nights, long fading periods were seen. This fading phenomenon, although better understood at the present time, is still the subject of many studies.

It is interesting to note that the first successful long-distance, multihop, multichannel microwave radios were digital radios. Thirty years were to pass before digital radio would see extensive applications.

As a result of the successful AN/TRC-6 program, the ATT microwave relay work, which was abandoned in 1939, was started again and was to be one of the leading programs at Bell Labs in the early post-war years.

VII. Early Post-War Microwave Radio

A bold proposal was made in the summer of 1943 to ATT management [29], before completion of the AN/TRC-6 program, to set up a large microwave radio relay demonstration from New York City to Boston. The system was to interface with a coaxial system from New York to Philadelphia, Baltimore, and Washington, D.C., and would serve as a definitive comparison of radio relay and coax. Approval to start the project was granted at the end of 1943. The radios were to have the capacity to relay two broad-band radio channels in two directions. Each radio channel was to have the capacity for up to 500 multiplexed telephone circuits, or one black-and-white television signal. The frequency selected was the 3.7 to 4.2-GHz band. Site acquisition for repeaters and development of the equipment was started in 1944. Engineers were assigned to the project as war efforts were completed. The system was formally opened in 1947. Even at the time of its inauguration, work was under way to extend the system to Chicago and, eventually, to the West Coast.

Eight repeaters with an average spacing of 27.5 mi were used in the 200-mi path. The route was designed using the information derived from extensive testing of the AN/TRC-6 paths, and other propagation tests. The analysis of the radio paths and the system were performed according to the formulation described by H. T. Friis [30]–[32]. Obstruction clearance on the radio paths was at least one Fresnel zone.

The system [33] was designed to accommodate frequency, amplitude, or pulse modulation, although the primary usage was FM. The two received radio channels at a repeater were separated in frequency by waveguide filters and sent to the two microwave receivers. A waveguide-balanced down converter with a silicon detector diode was the first stage of the receiver and operated with a 14-dB noise figure. The 65-MHz IF signal was amplified in a 7-stage AGC IF amplifier. A transmitter up converter, similar to the down converter, translated the IF signal back to the microwave range. A temperature-controlled, 4-stage klystron transmitter power amplifier was used to amplify the signal and to deliver about one watt to the antenna after filtering at the output frequency. A single microwave generator using a reflex klystron was stabilized with a high-Q invar cavity and servo control of the repeller voltage. An appropriate offset frequency was used to provide local oscillator power to both the up and down converters. Waveguide was used to connect the antennas to the microwave equipment located in shelters at ground level. Separate receivers and transmitters were used in each direction at a repeater site. The antennas were the shielded-lens type with a square aperture, 10 ft on a side, and provided 39-dB gain. The system was powered with 230-V ac commercial power.

Excellent performance was achieved, as the system was equal to or better than the coaxial system.

Experiments were conducted connecting the four paths in tandem, thus simulating an 880-mi path. The television transmission over the long path met specifications. The voice circuit transmission measurements indicated that toll quality was achieved with up to 240-voice circuit loading.

Following the successful implementation of the New York–Boston system, work was started at ATT on a 4-GHz transcontinental network, the TD-2 system [34]. The TD-2 system was designed with a capability of expansion to a 4000-mi overall path length with 125 repeaters spaced 25–30 mi apart. The TD-2 system was initially designed for each radio to have a capacity of hundreds of voice circuits or one black-and-white video picture. Compatibility with existing facilities (coax, wire line, etc.) had to be maintained. By the end of 1951, over 20 000 radio channel-miles of microwave were in operation for the Bell System. Two-thirds of the capacity were used for television transmission and one-third for over 600 000 telephone voice circuit-miles.

The TD-2 system used FM and had 12 radio channels, six in each direction. Each transmitter and receiver was spaced 40 MHz apart in the 3.7 to 4.2-GHz common-carrierband. A repeater typically received a signal with a level of −38 dBm and retransmitted at +27 dBm. Upward fades of +5 dB and downward fades of 25 dB were compensated by IF AGC. The receiving waveguide branching circuitry separated the 20-MHz-wide channels in the incoming composite signal and delivered the appropriate signals to one of the six receivers. The separator was two hybrid junctions and two band reflection filters tuned to the band to be separated. The down converter was a balanced waveguide circuit with silicon detectors and a 70-MHz IF.

The transmitter amplifier was based on newly developed close-spaced microwave triodes. These were used in place of the higher voltage klystrons in the earlier 4-GHz radio. The triode was designed to be easily coupled to grid-cathode and grid-plate cavities. The up converter also used the triode. The IF signal was applied to the grid and local oscillator drive was applied to the grid-cathode cavity. The output of the modulator was used to drive a three-stage microwave triode amplifier with 18-dB gain and an output level of 0.5 W.

As with the earlier radio, a common-microwave generation system was used for the transmitter and receiver. A harmonic generator using a crystal-controlled 18-MHz oscillator followed by three doublers and three triplers replaced the earlier klystron and provided 200 mW to drive the up and down converters. A photograph of a TD-2 radio is shown in Fig. 2.

It was possible to use battery power on the TD-2 in place of the earlier commercial AC power since the triodes operated at considerably lower voltage than the klystrons. This resulted in an improved lower noise power system. A full alarm and monitor system was designed to allow unmanned operation of the repeaters. Towers as high as several hundred feet were used in the system. The New York-to-Chicago path used concrete towers, primarily because of the availability of materials in 1948 and 1949. Steel towers were used in the Omaha-to-San Francisco path, which was completed later.

In addition to the microwave repeaters discussed above, FM modems located at the terminal sites, frequency modulated a 70-MHz carrier with either frequency division multiplexed voice circuits, or a black-and-white television signal. The terminal equipment also demodulated a received 70-MHz modulated signal. A long system, such as TD-2, requires terminal sites fairly frequently, to drop and insert message groups. To maintain high-quality transmission without introducing intermodulation distortion effects, it was necessary to maintain extreme linearity in the FM equipment. Long haul objectives were to be met with 16 pairs of terminals in tandem. The linear 70-MHz FM transmitted signal was generated by a microwave heterodyne scheme. The baseband video or multiplexed message

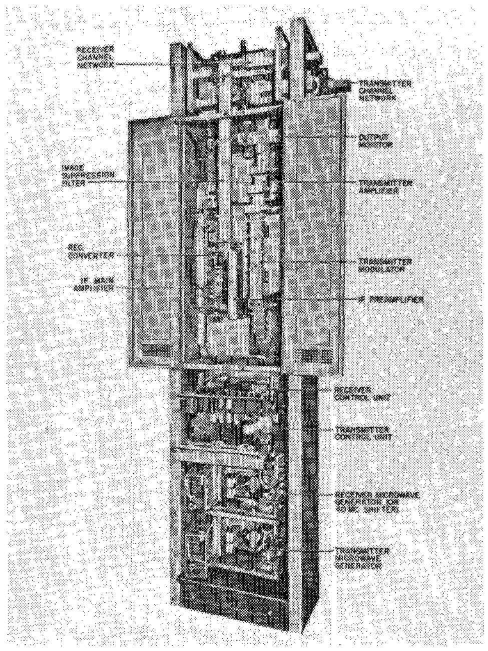


Fig. 2. Microwave repeater bay, TD-2 system (Reprinted from the *Bell Syst. Tech. J.* Copyright 1951, AT&T).

signals were applied to the repeller of a 4-GHz klystron to create a linear deviation over a 10-MHz frequency range. The modulated 4-GHz signal was then heterodyned with a 4-GHz CW signal generated by a second klystron to produce the linearly modulated 70-MHz signal which serves as the input to the transmitter. The FM receiver terminal consisted of an IF amplifier and a discriminator.

The TD-2 system has been in service since 1951. It has been upgraded and rebuilt several times. The original components were replaced over the years and the system now includes solid-state sources, GaAs FET power amplifiers, and all solid-state circuits.

During the early 1950's, a very significant advance in microwave tubes, the traveling-wave tube, was introduced into microwave communication systems. The traveling-wave tube was invented during World War II by Rudolph Kompfner at the British Admirality. The tube was perfected at Bell Labs in 1947 by Kompfner, who had immigrated to the United States, and J. R. Pierce [35]. This tube allows continuous interaction between an electron beam and a slow electromagnetic wave traveling on a helical waveguide. Transfer of energy from the beam to the electromagnetic wave provides high gain over broad bandwidths. The traveling-wave tube was first applied to a microwave radio by ITT in 1952, and has had very extensive application in microwave radio relay through the present time.

The application of radio relay in common-carrier systems grew rapidly in the 1950's and 1960's, both in new technology and also in volume. Many companies in the United States and elsewhere entered the business of developing and manufacturing microwave radio for telephone companies, private users, such as railroads, pipeline, federal, and state systems. Radios in the 2-, 4-, 6-, 8- and 11-GHz

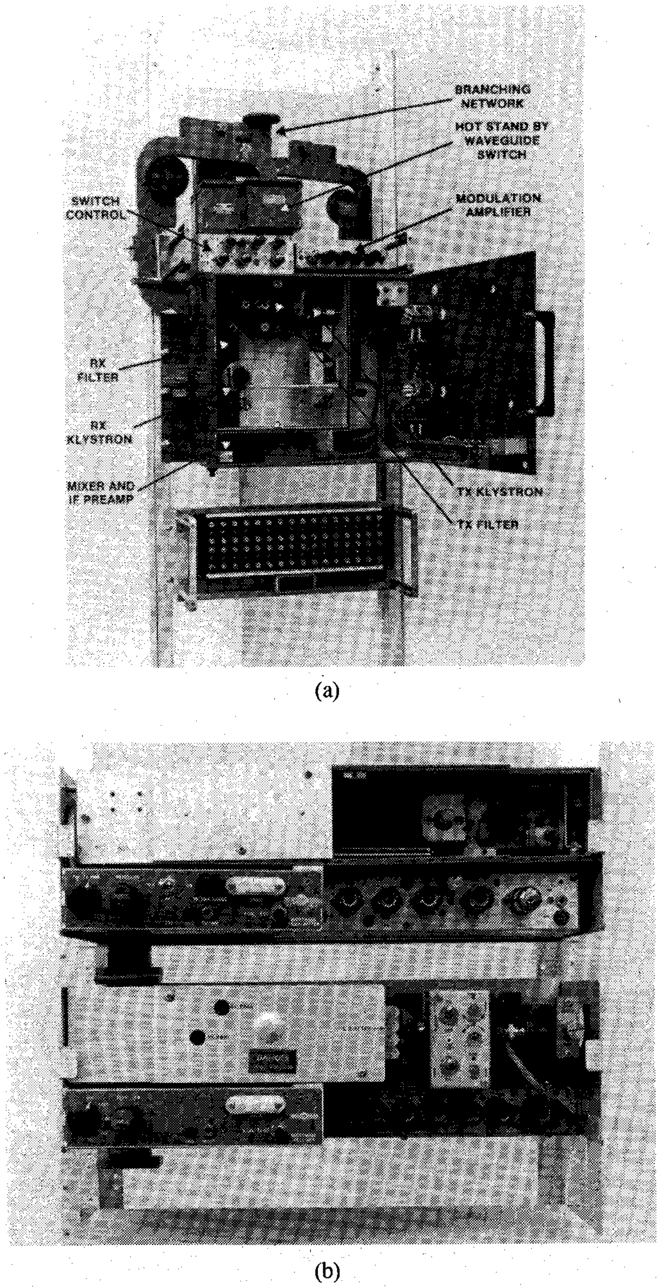


Fig. 3. Collins radio MW101 remodulating radio, (a) transceiver, and (b) alternate configuration of receiver and transmitters (MW102).

bands were developed and widely used [36], [37]. The 4-GHz nationwide system for ATT was overbuilt with a 6-GHz system. Another very large nationwide network was built by the FAA for radio relaying enroute air traffic control radar information to the principle control centers in the United States. This system utilized Collins Radio 8-GHz microwave radios. Early equipment for this system utilized klystrons, while later radios incorporated traveling-wave tubes.

An example of an early 1950's radio, the MW101 built by Collins Radio, is shown in the photograph in Fig. 3. The MW101 operated in the Common Carrier 5.9 to 6.4-GHz band and was used for systems with low density and relatively short overall lengths. Another version of the radio, the MW302, operated in the 6.4 to 6.8-GHz Operational Fixed Band for private systems. The capacity of the radio was 120 voice circuits. The long haul radios described above for nationwide networks were heterodyne radios, wherein the repeater down converted the signal to IF, amplified at IF, up converted to the transmit frequency, and amplified to the required output level. The repeaters do no demodulation or remodulation of the signal. The low-density systems, such as the MW101, are remodulating radios that use no up converter translation but do demodulate the signal at a repeater to baseband and remodulate the transmitter. The cost of the remodulating radio is lower than the cost of the heterodyne radio, but the penalty is performance.

The MW101 utilized reflex klystrons for the modulatable transmitter oscillator and the receiver local oscillator which drives the down converter. The transmitter power was 150 MW. The IF frequency was 60 MHz. The equipment was powered by a 115-V AC source or a 130-V battery system.

VIII. Modern Microwave Radio

Microwave radio systems have undergone very significant improvements and changes during the 30-year period following the introduction of the radios described in the previous section. A tremendous volume of radios have been manufactured and applied in the U.S. and elsewhere. Today, there are at least *70 000* FCC licensed microwave transceivers operating in the U.S., providing nearly 750 million voice circuit miles of service.

New microwave technology introduced during the 30-year period has been the primary driver in the performance improvements. Microwave ferrites have made possible extremely stable components, alleviating shifts, due to load changes and have also significantly improved waveguide branching networks. Traveling-wave tubes proved to be reliable power amplifiers that provided excellent performance. Solid-state devices were first introduced in IF, baseband, and control circuits, and were very successful in achieving excellent performance. Microwave silicon bipolar transistors were first used as oscillators, followed by silicon and GaAs varactor diode multipliers to reach the final operating frequencies. Microwave silicon transistors were also used as amplifiers in the sources and as power amplifiers in 2-GHz radios. GaAs Schottky barrier mixer diodes were used to achieve low noise performance. Gunn diodes were introduced as oscillators and IMPATT diodes for amplifiers. In the 1970's, GaAs FET's were applied in receivers to achieve extremely low-noise front ends and also for transmitter power amplifiers in the 4- and 6-GHz bands.

Waveguide circuits were replaced by microwave integrated circuits using microstrip or other circuit forms on teflon-based, or ceramic, substrates. Dielectric resonators were used as high-Q resonators for oscillators and filters. As the operating range of transistors was increased to higher frequencies, fundamental sources, operating directly at the final frequency, were developed [38]. Space and frequency diversity, and multiline switching systems, were

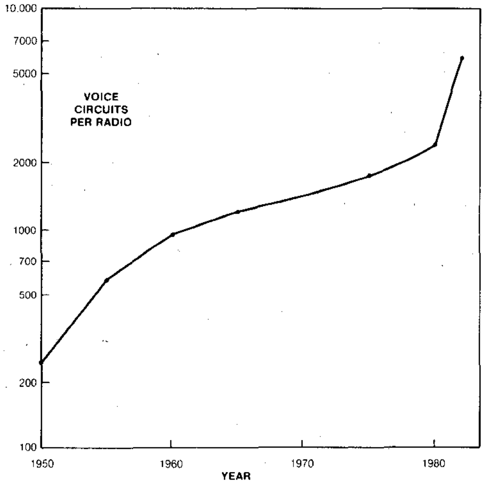


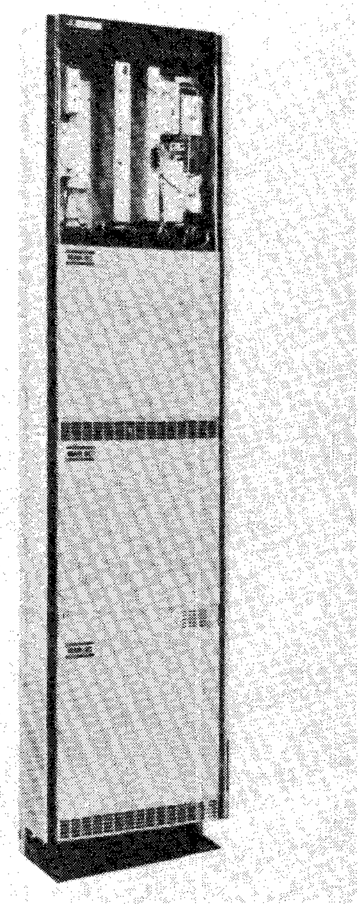
Fig. 4. Voice circuit capacity of analog microwave radio, 1950–1983.

introduced to provide very reliable operation with protection against equipment failure and path fades. Many years of research on propagation effects at microwave frequencies provided the understanding of atmospheric anomalies and led to the development of various fading countermeasures, including the above, as well as adaptive equalizers.

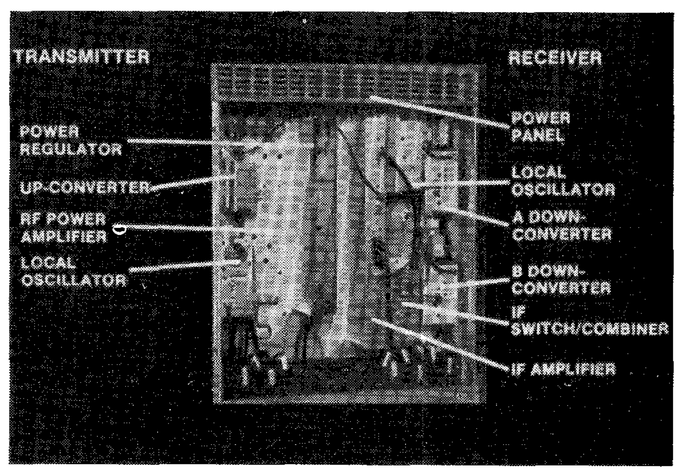
The increase of the capacity of microwave radios made possible by the above technologies is shown in Fig. 4. An example of a modern 6-GHz, 2400 voice circuit all solid-state heterodyne FM radio is shown in Fig. 5. This radio, the MAR-6C [39], manufactured by Collins Transmission Systems Division of Rockwell International, uses a 5-W, 37-dB gain GaAs FET power amplifier, a GaAs low-noise 6-GHz receiver preamplifier, fundamental sources using a 6-GHz silicon bipolar transistor, and a directly modulated source for terminal applications. The radio makes extensive use of hybrid integrated circuits. The seven-foot-high bay shown in Fig. 5 contains four transmitters and eight receivers. The MAR-6C has 50 percent higher voice circuit capacity, occupies one-fourth the volume, uses one-third the prime power, and has five times the reliability of a similar FM radio built in 1973.

Frequency-modulated, frequency-division multiplexed radios have been the predominant type of microwave radios used since the 1940's. The extensive application of these radios has led to very high congestion in certain areas of the country and further expansion using FM radio is not possible. In addition, the introduction of digital switching, the growing use of PCM, and the tremendous growth of data communications has led to the need for digital transmission. As a consequence, in a recent years extensive effort has gone into the development and deployment of alternative forms of microwave radio, single-sideband AM radios, and digitally modulated radios.

Single sideband modulation has been used in long-distance HF and VHF low-density applications for many years. The potential for use in very high-density microwave communication systems was recognized early in the 1970's, and was studied for many years. One of the primary limitations in applying SSB modulation was the unavailability of linear microwave functions. These devices have now been developed and SSB microwave radios are being placed into service. The use of IF predistorters for correcting nonlinearities in the entire RF chain has played a major role in advancing SSB. Bell Labs conducted an intensive study and development program on SSB, and ATT started field installations of the AR6A, 6-GHz, 6000 voice circuit capacity radio in the late 1970's [40]. A second SSB radio, the MSR-6, was developed and is being pro-



(a)



(b)

Fig. 5. Rockwell International MAR-6C, 2400 channel FM radio, (a) radio bay, 4 transmitters, 8 receivers, (b) enlargement of one MAR-6C transceiver.

duced by Rockwell International [41]. Field installation of the MSR-6 was started in 1983. This radio also operates in the 6-GHz common-carrier band and has a 5400 voice circuit capacity. Configurations of the radio are possible that allow an earlier Rockwell FM radio, the MW109E-1, to be retrofitted for SSB operation with an increase of capacity from 1800 FDM voice circuits to 5400 circuits.

As pointed out earlier, one of the first production microwave radios, the AN/TRC-6, was a digital radio, but 30 years were to pass before digital radios would again play a role. Although Nippon Electric Company delivered digital radios to New York Telephone Company and DATRAN Corporation in the early 1970's, it was not until 1974 that the FCC issued the Regulatory Notices governing microwave digital transmission in the U.S. common-carrier bands. The common-carrier digital radios interface with the *T*-carrier pulse code modulation, time division multiplex hierarchy in the U.S., and the CEPT hierarchy in most other areas of the world. Early digital radios in the U.S., following the definition of regulations by the FCC, utilized QPSK modulation and transmitted two 45 MB/s channels, on orthogonal polarizations at the same frequency. This system proved to be ineffective during fading conditions because of the loss of cross-polarization discrimination. 8-PSK systems [42] that operated at 90 MB/s on a single polarization, in the 30-MHz-wide, 6-GHz common-carrier band, and in the 40-MHz, 11-GHz band were developed. The 8-PSK radios represent the majority of digital radios currently in use.

A disadvantage of digital systems is spectrum capacity. The 90 MB/s radio has a capacity of 1344 voice circuits (56 T-1 circuits), about one-half the channel capacity of FM radios in the same band. Digital radios utilizing higher level modulation schemes than 8-PSK are being introduced to increase capacity. These new radios, which use 16 QAM (16-level quadrature amplitude modulation) and 64 QAM [43] schemes, result in significant improvements. The 16 QAM radio can achieve an increase of capacity of 50 percent at 11 GHz compared to an 8-PSK radio. The 64 QAM radio can achieve increase in capacity of 50 percent at 6 GHz, and 100 percent at 11 GHz. Thus, the new digital radios will have capacity comparable to FM radio, but are a far cry from SSB equipment.

The above discussion relates primarily to radios operating in the high-density common-carrier bands. Radios operating at 2, 10, 18 and 22 GHz have been developed for low-density routes, spur routes, and local distribution. Application of these radios may grow significantly in the future. Radios operating as high as 39 GHz have been developed for Electronic News Gathering for Television news service.

We will now turn to a brief review of waveguide and satellite communication systems.

IX. The Waveguide Communication System

The waveguide transmission work started by Southworth, and described earlier, was given emphasis at Bell Labs during the post-war years. The discovery of the decreasing attenuation property of the circular waveguide TE_{01} mode led researchers to propose a millimeter waveguide system. Initial efforts were directed towards the development of wide-band traveling-wave tubes operating in the 50-GHz band. Many technical problems were encountered and overcome in the fabrication of the very small helices and other components of the tube. However, it was not until the late 1960's and early 1970's when millimeter-wave IMPATT diodes were developed that a practical implementation of the millimeter wave system was conceived.

Methods of mode control in the waveguide itself had to be developed to prevent conversion from the low-loss TE_{01} mode to the higher loss TM_{11} mode, which is degenerate with the TE_{01} mode. The major cause of mode conversion is bends in the waveguide. A thin dielectric coating on the waveguide wall removed the degeneracy. The helical inner-wall waveguide was used as a filter at 800-m intervals to reduce conversion to the TE_{12} and the TM_{11} modes. Losses over 20KM sections of waveguide were found to be less than 1 dB/KM from 40 to 120 GHz for a waveguide with a diameter of 60 mm.

An ambitious program [44] to develop a digital system that had a capacity of 230,000 duplex voice circuits over the band from 40–110 GHz in a single waveguide was undertaken. This was to be achieved by using sixty 274 MB/s data streams for each direction of propagation. Millimeter wave components including silicon IMPATT oscillators, receivers, modulators, diplexers, 1.3-GHz IF amplifiers, and waveguide equalizers were developed. Trial sections of waveguide were built and tested. A 10-KM waveguide system was installed as a trial system in Netcong, New Jersey. In a complete installation of the system, repeaters would be spaced every 25 km. Tests on the New Jersey system ran through 1976. Millimeter waveguide systems were also built for trial systems in England, France, Germany, and elsewhere.

During this time, development of fiber-optics systems was started. It soon became apparent that the optical system offered considerably more potential for lower cost systems and work on the waveguide communication system was abandoned in the late 1970's.

X. Satellite Communication Systems

Satellite communication systems are an outstanding successful example of the application of microwave technology. The first proposal for the use of synchronous satellite repeaters was by Arthur C. Clarke in an article in *Wireless World* entitled "Extraterrestrial relays" in 1946. Clarke addressed the use of the repeaters for wide-coverage FM broadcast rather than for duplex communication systems. One of the earliest steps towards satellite communications was an experiment conducted by the U.S. Army Signal Corps in 1946 when radio signals were bounced off the moon and were successfully detected on earth. Experiments on the moon bounce continued through the 1950's, with the first voice message path established by the US Navy in 1954, and a permanent relay service established between Washington, D.C., and Hawaii in 1956. The latter used 430-MHz propagation with 100-KW transmitters and 26-m-diam antennas [45].

J. R. Pierce [46] of Bell Labs proposed the concept of communication satellites for telephony in a talk to the Princeton Section of the IRE in 1954. He considered active and passive repeaters and orbiting as well as synchronous satellites. The application of satellites was more fully discussed in a 1959 paper [47]. Progress in the development of rocketry and space vehicles enabled the test of a passive repeater in space, the ECHO satellite (a plastic, metal-covered balloon) at an altitude of 1500 KM, in 1960, for communications between transmitting and receiving stations in New Jersey and California at frequencies of 0.96 GHz and 2.3 GHz.

A severe problem with passive repeaters was that, in systems such as the ECHO relay, only one part in 10^{18} of the transmitted power is returned to earth. Fortunately, MASERS were available in 1954, with noise temperatures of 10°K and, when used with extremely high gain 43 M^2 antennas, reasonable transmission performance could be obtained. However, it was clear that active satellites would offer considerably improved, high-capacity service.

The first active U.S. communication satellite, a broadcast system called SCORE, was launched in December 1958, and transmitted President Eisenhower's Christmas message to the world with a satellite power of 8 W at 122 MHz.

In July of 1962, the Telstar active satellite built by ATT was launched. This orbiting satellite which used a 6-GHz up-link and 4-GHz down-link was used for television transmission, and for demonstrations of telephony between American and European cities.

The transmitter power of Telstar was 2.25 W. The first successful synchronous active satellite, Syncom 111, built by Hughes Aircraft, was placed in orbit in 1964. The first commercial communication satellite, Early Bird built by Hughes Aircraft Company, was placed in orbit in April 1965, and provided 240 telephone circuits and television transmission between the U.S. and Europe. By 1973, more than eight synchronous satellites stationed over the Atlantic, Pacific, and Indian Oceans beamed telephone, television, telegraph, and facsimile signals to ground stations in 39 countries. The capacities of satellites of this era, such as INTELSAL IV, had increased to about 6000 telephone circuits or 12 color-TV channels. The satellite systems increased the number of transoceanic voice circuits from 1000 in 1957 to more than 25,000 in 1973.

The first North American domestic satellite, Canadian ANIK, was launched in 1972, and the first U.S. domestic satellite, WESTAR, was launched in 1974. Today, there are 16 C-band (6-GHz up-link and 4-GHz down-link) and three Ku-band (14-GHz up-link and 12-GHz down-link) satellites serving the U.S. domestic market. A modern satellite has up to twenty-four, 36-MHz-wide transponders, each with an EIRP equal to 34 dBW.

Various forms of modulation are used in satellite systems. FM/FDM with a single channel per carrier (SCPC) system can result in a capacity of 1800 voice circuits per transponder, or more than 40,000 voice circuits if all 24 transponders are used. Domestic satellites usually use one transponder per video signal. Other forms of modulation, including phase shift keying with either PCM or delta modulation, are used in single-carrier per transponder or in time division multiple-access configurations. SSB is also under study as a possible approach to increase the capacity of the transponder. A full discussion of satellite system technology is beyond the scope of this paper.

The advances in satellite communications were made possible by greatly improved technology for space vehicles and significant advances in microwave components for satellite and earth station applications. Long-life reliable traveling-wave tubes have been deployed in most satellites, but recently GaAs FET power amplifiers have been used. Significant improvements in microwave filters and antennas and the development of low-weight microwave components have contributed significantly to the advances in satellites. Earth station technology has changed very significantly from the early systems that used MASER's. Low-noise cooled paramps were used to achieve noise temperatures close to the levels provided by MASER's. These were followed by a second-stage GaAs FET low-noise amplifiers. Today, video receive-only stations and low-density small earth stations for data communication use GaAs FET's as the low-noise amplifiers.

Early commercial satellite systems operated primarily in C-band. Ku-band satellites have already been launched and will be more popular in the future, particularly in view of the move to reduce the spacing between satellites to 2°. Eighteen Ku-band satellites and five C-band satellites are planned for launching between now and 1987 to serve the U.S. domestic market. Ka-band satellites operating at 30 and 20 GHz are being studied, but none are in commercial use at this time.

XI. Conclusions

This paper has addressed some of the major types of microwave systems. Other important areas, including troposcatter radio, have not been covered.

The past 100 years have witnessed the growth of a communication technology that started with a theoretical prediction that electromagnetic energy propagates as waves and has progressed to the development of sophisticated nation-wide and world-wide systems, as well as space communications. This communication revolution has had tremendous impact on the world's societies. It is difficult today to imagine life without the long-distance communications made available by microwave systems. It would probably be just as difficult for the early pioneers in the radio field to imagine the progress that their discoveries and inventions have produced. The day is not far away when microwave receivers for use with video transmission by the Direct Broadcast Satellite will be located in the homes of a significant percentage of the earth's population.

Acknowledgments

The preparation of this paper has been a very interesting and rewarding experience for the author. Too often, work in a small area for a short time dims one's view of the

exciting and challenging history that led to a current state-of-the-art.

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Most of all, the author is grateful to the late G. Southworth for documenting his outstanding and productive career in his book *Forty Years of Radio Research*. This book should be read not only by workers in communications and microwave, but all those contemplating or active in a career in research.

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Dr. Sobol was first elected to MTT Society Ad Com in 1972 and has served as Chairman Technical Committees, Vice President, and was elected President for 1978. He served as General Chairman of 1974 Electronic Components Conference and of 1975 International Solid-State Circuits Conference. He has been a member of the Program Committees of the above and of the MTT Symposium since 1968. He was Vice-Program Chairman of 1973 IEEE Intercon. He was IEEE Microwave National Lecturer in 1970. He was the recipient of an IR-100 award in 1969 for his work on microwave integrated circuits and received the Dallas IEEE Section Award for Outstanding Engineer of 1975.