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WT4 Millimeter Waveguide System:

The WT4/WT4A Millimeter-Wave Transmission System

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The WT4/WT4A millimeter-wave, long-haul transmission system is described. The description includes overall characteristics of the various system components, their interrelationship, and performance. Results of the field evaluation test are summarized.

I. INTRODUCTION

The WT4/WT4A communication system is designed to provide long-distance communication service at a lower per circuit cost when fully loaded and with an order of magnitude higher reliability then has been achieved previously in right-of-way systems. In the WT4 version, capacity is almost two times that of any existing system, and in the WT4A version, capacity is twice that of WT4. Digital signal transmission is used which can accommodate any mix of voice, high-speed data, TV, and *PICTUREPHONE®* service. The system can be installed readily on any terrain and any right-of-way. Methods and procedures have been developed for easy low-cost maintenance.

II. GENERAL DESCRIPTION

The WT4/WT4A system uses 60-mm internal diameter waveguide as the transmission medium. It is designed to provide a total of 124 broadband channels of which 59 are used for signal transmission and three for protection in each direction. The specific designs of the experimental system described in this paper and the companion papers in this issue operate in the 40- to 110-GHz frequency band.

Based on the results of a field evaluation test conducted in northern New Jersey from 1974–76, the frequency band is being shifted to 38–

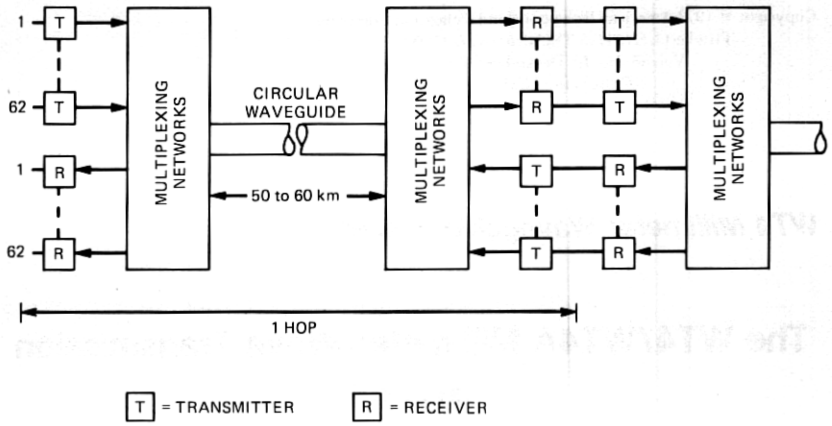

Fig. 1—Block diagram of a repeater hop.

104.5 GHz to maximize the repeater spacing using 60-mm diameter waveguide. The repeater spacing for commercial systems will be a maximum of approximately 60 kilometers (37 miles) in relatively gentle terrain and on superhighway rights-of-way. In very rugged terrain, such as the mountains of Pennsylvania, the maximum repeater spacing will be reduced to about 50 kilometers (31 miles).

The system uses solid-state regenerative repeaters which carry a DS-4 digital signal stream (274 megabits per second). The system error rate is less than 10^{-7} for 6000 kilometers (4000 miles) transmission distances and a service availability of better than 0.9998. On initial installations (WT4) two-level, differentially coded, phase-shift-keyed modulation can be used to furnish up to 238,000 two-way voice circuits. As traffic demand increases, the system may be upgraded to four-level modulation (WT4A) up to a total capacity of 476,000 voice channels. This increased capacity can be achieved without changing repeater spacing by retrofitting only the electronics. To allow system management flexibility, as many as six of the repeater stations within a protection span [up to 500 km (300 miles)] can be arranged to add or drop signal channels.

A block diagram of one fully equipped hop or span of the system is shown in Fig. 1. Sixty-two transmitters which operate at different millimeter-wave carrier frequencies in one-half of the frequency spectrum carry east-west signals to 62 receivers at the next repeater station. Correspondingly, another set of 62 receivers and transmitters carry west-east signals in the opposite direction in the other half of the frequency spectrum. A multiplexer connects the 124 individual channels to the single waveguide broadband transmission medium.

An important system feature is that the multiplexing network configuration and the waveguide parameters are selected so that their total

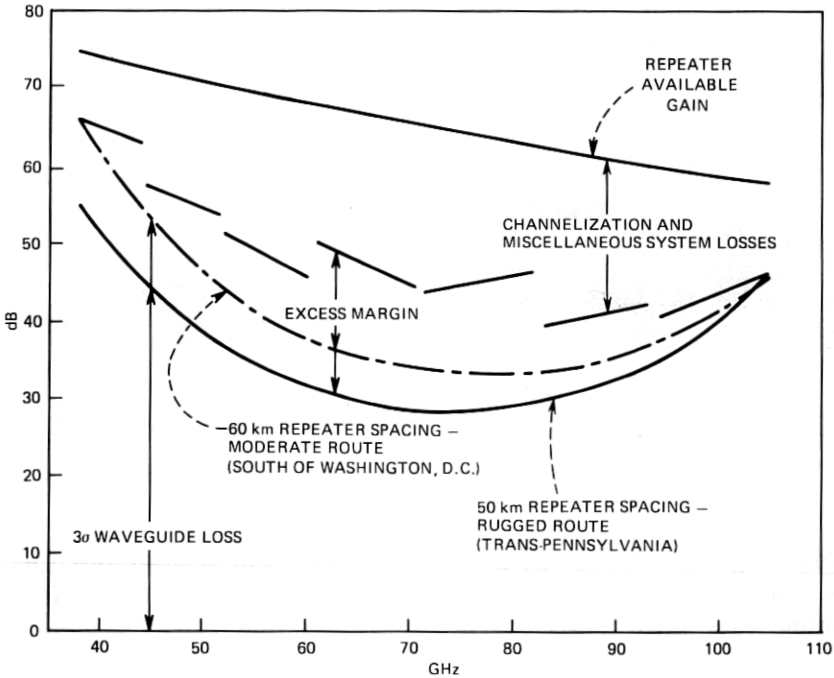

Fig. 2—WT4A system loss composite.

loss-versus-frequency characteristic closely matches the available gain and noise-figure-versus-frequency characteristic of the repeaters.

Figure 2 shows the individual and combined loss design parameters of the commercial WT4A design for repeater station spacings of 50 kilometers for the difficult terrain of the trans-Pennsylvania route and 60 kilometers for the moderate terrain model typical of routes on the United States East Coast south of Washington. 3σ values are used for the installed waveguide losses.

The overall loss budget shown also includes a 3-dB margin to accommodate repairs and future route realignments. The loss ceiling or available repeater gain curve in Fig. 2 is based on having a transmitted power 10 dB lower at 104.5 GHz than at 38 GHz and on having the receiver noise figure 3 dB higher at 104.5 GHz than at 38 GHz.

Because of the large traffic-carrying capacity, the highest possible reliability and service availability are important features. High reliability in the electronics is achieved by operating solid-state circuits in a dry nitrogen environment. The large distance between repeaters minimizes the number of repeaters required and therefore also contributes to service availability. The transmission medium is extraordinarily resistant

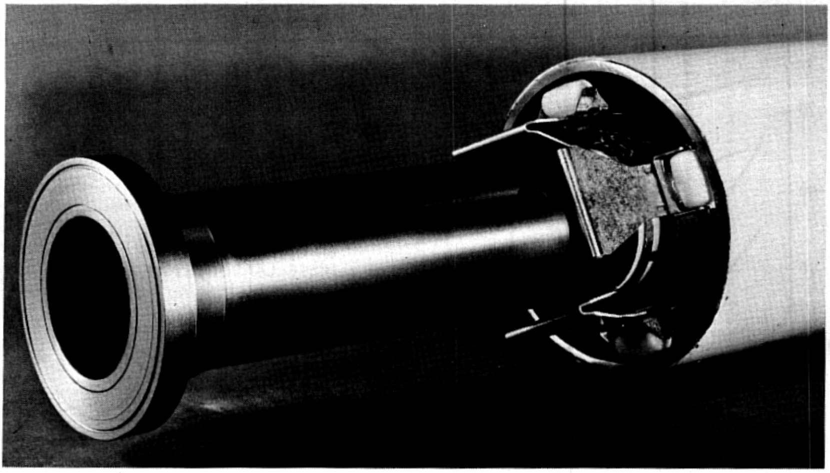

Fig. 3—Waveguide with flange, spring roller supports, and steel sheath.

to damage since its basic structure is made up of fusion-joined steel tube sections encased in a fusion-joined protective steel outer casing. It is impervious to lightning damage and highly resistant to damage from most construction machinery which often causes damage to other buried communication systems. Restoration methods have been developed even for the rare cases where a waveguide failure should occur. To enhance the reliability, no manholes or expansion joints interrupt the transmission medium between repeater stations. The overall built-in reliability is such that minimal routine maintenance is anticipated.

Because the reliability of the waveguide medium is so much higher than that of a buried cable, it is also used to carry the protection-system signaling and order wire. These are interleaved into the digital data streams of designated channels. Should a service channel fail, automatic transfer to a protection channel is provided.

Particular attention was paid in the design of the waveguide medium to provide for easy installation on any commercially feasible right-of-way. Conventional pipeline construction methods are used, and the waveguide has been designed so it can follow the horizontal bends and vertical contours of the right-of-way without undue performance penalties.

Because of the heavy shielding provided by the sheath and the waveguide, even high-voltage power line rights-of-way can be utilized without incurring any interference.

Protection against electromagnetic radiation to and from outside sources is of increasing concern in the design of new systems. In the WT4 repeaters all parts that carry radio-frequency and intermediate-frequency signals are shielded. Since the radio-frequency signals in the

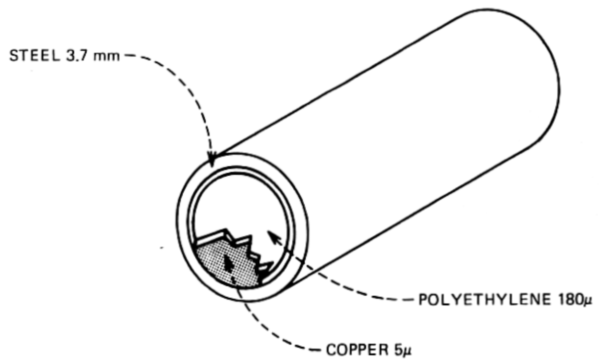

Fig. 4—Dielectric-lined waveguide.

multiplexer networks and circular waveguide are also shielded, the WT4 system causes no radiation pollution.

The repeater stations[1] are above-ground buildings spaced up to 60 kilometers apart, as stated previously. They also contain the various auxiliary services needed to operate the repeaters, protection switching, etc. They are powered from commercial sources, but self-contained emergency standby power is provided. The system is safe for maintenance personnel since no high voltages are required for any of the active circuits.

In the remainder of this paper, we will first discuss some salient features of the waveguide medium, its installation, reliability and maintenance. This will be followed by discussion of the multiplexers, repeaters, protection switching, order wire, and telemetry, and the results of the field evaluation test.

III. THE WAVEGUIDE TRANSMISSION MEDIUM

The transmission medium for the millimeter wave system is a waveguide with a circular cross section of 60 mm (~2 3/8 in.) inside diameter. Supported by spring roller supports, it is installed in a 140-mm (5 1/2 in.) outside diameter steel sheath buried a minimum of 0.6 meter (2 ft) below the surface. Individual sections of waveguide as well as the sheath are joined by fusion welding. The waveguide with its flange, spring roller supports, and steel sheath are shown in Fig. 3. The installed waveguide consists of a mix of 99 percent dielectric-lined guide and 1 percent helix-type mode-filter guide. The dielectric-lined guide has an inner conducting surface of plated high-conductivity copper and a thin polyethylene lining (Fig. 4). The helix guide consists of a layer of millimeter-wave-absorbing material and a copper helical structure inside the steel tube (Fig. 5). This combination of waveguide types provided a total installed loss below 1 dB/km from 40–110 GHz on the field evaluation test route.

To achieve the lowest installed loss in the design of the waveguide, two loss mechanisms must be considered. One is the heat (resistive and dielectric) loss which is controlled by choice of waveguide diameter and by the quality of the manufacturing process. The second is the so-called mode conversion loss. Since the waveguide is much larger in diameter (60 mm) than the wavelengths of the signals in the system (2.7–7.5 mm)

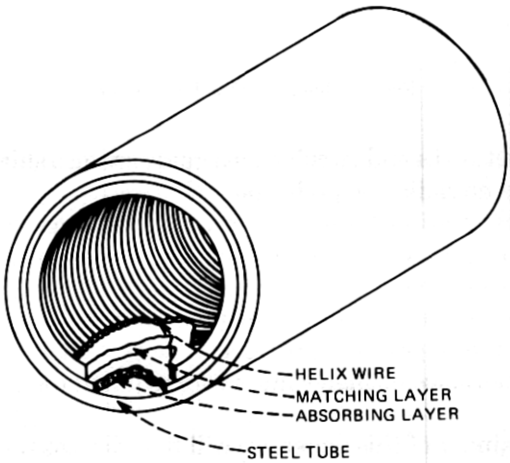

Fig. 5—Helix waveguide.

electromagnetic energy can propagate in many field patterns called modes. Only one of these, the TE_{01} mode, has the low-loss transmission property desired. When signal energy is converted from the TE_{01} mode to any of the other modes some additional signal loss results. This energy transfer and consequent loss is minimized by the dielectric liner applied to the guide,[2,3,4] by proper controls of the manufacturing process, and by the installation design and route engineering. In the following, the various losses are examined in some more detail. The addition of the various loss components is shown in Fig. 6.

3.1 Heat loss

In Fig. 6, curve a is the idealized loss curve for intrinsic pure copper. For various reasons, such as conductor impurities, surface roughness and dielectric-liner-induced losses, this ideal is not attained in practice.[5] The heat loss which was achieved consistently under manufacturing conditions for the field evaluation test is shown in curve b, Fig. 6. This loss is about 0.06 dB/km higher than the ideal at 40 GHz.

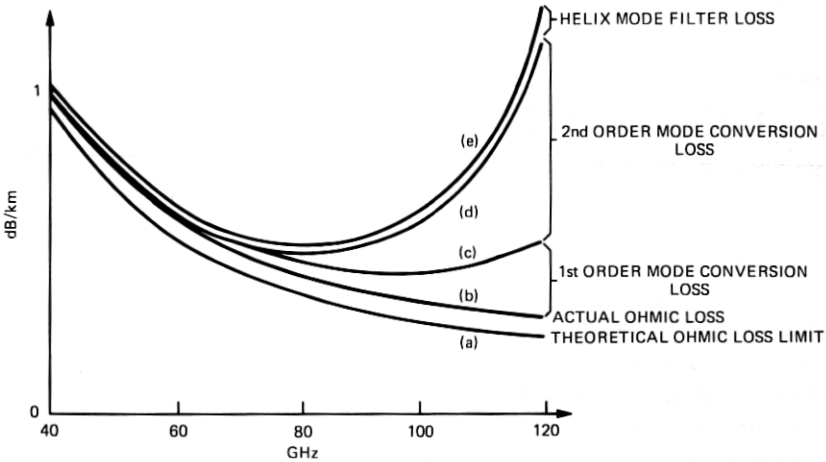

Fig. 6—Addition of the various loss components.

3.2 Mode conversion loss

Mode conversion results whenever the geometry of the waveguide departs from a perfectly true cylinder. The three principal sources of geometric distortion are:

(*i*) Manufacture of the waveguide
(*ii*) Installation
(*iii*) Horizontal and vertical route bends

Since it is easier to control tolerances in a factory environment than in the field, much of the mode conversion control is achieved by attention to waveguide design details and by careful design of factory processes, tooling, and inspection. To avoid excessively stringent tolerances, advantage was taken of the theoretical understanding of the relation between waveguide geometry and mode generation.[6]

The geometry of the waveguide is inspected in the factory by mechanical gauges which rapidly measure the waveguide distortions. As the data are being taken they are fed into a minicomputer for evaluation of their level of distortions and particularly their periodic components. The computer outputs are simple go, no-go displays for the machine operator and inspector.

The application of minicomputer-aided inspection as part of a manufacturing specification has resulted in an excellent yield of high-grade waveguide-quality tubing and finished product at reasonable cost using only slight modifications of standard manufacturing processes, as described by Boyd et al.[5]

The installation process adds distortions on top of the manufacturing distortions and also contributes to unwanted modes. Modes caused by trench bottom irregularities are reduced by suspending the waveguide on spring roller supports inside the protective steel sheath. The steel sheath and spring supports in conjunction with the stiffness of the waveguide act as mechanical filters between the waveguide and trench bottom irregularities.[7] Other important sources of installation distortion are tilt and offset of the waveguide flanges. These are controlled by the flange design, the manufacturing process, and by the tooling used in the field-weld joining process.

Another important potential source of periodic geometric distortions are diameter discontinuities at waveguide couplings which would generate undesired modes. The waveguide lengths are therefore pseudo-randomized by a small amount with a uniform distribution during the sizing process in the factory to avoid the cumulative effects of periodic coupling spacing.

Because of terrain features, changes in waveguide horizontal and vertical direction through bends are unavoidable. These bends will also generate various spurious modes. Energy coupling to these modes and loss are minimized by the dielectric lining and by the natural tapering of the installed waveguide bends. Bends with radii as tight as 75 m (250 ft) can be negotiated with minimal loss. The total mode conversion loss due to direct or "first-order" mode generation from these various geometrical distortions is shown added to the heat loss as curve c in Fig. 6.

During the field evaluation test an important mode generation mechanism was discovered in the interaction between several modes in the presence of tight horizontal or vertical bends and long mechanical periodicities of wavelengths in the order of 20 m (~65 ft). This is described in detail by Carlin and Moorthy.[8] These long wavelength periodicities are caused by the natural undulations of the terrain and are not filtered out by the sheath stiffness. The resulting mode generation increases as the sixth power of frequency and the fourth power of route curvature and is shown as added loss in curve d, Fig. 6. This rapid increase in mode conversion at the highest frequencies of the WT4/WT4A band when coupled with route curvature was an important finding of the field evaluation test. This provided a major incentive to shift the WT4/WT4A frequency band slightly downward for the commercial system which allows increased repeater spacing and makes route selection and engineering much easier.

3.3 Mode filtration

Even with optimal manufacturing and installation techniques a small residual level of excess unwanted modes must be suppressed. Helix guide[9] is therefore used as a mode filter. Since mode conversion losses in helix guide are particularly sensitive to bends in the installation, an important design objective is to minimize the amount of helix used and then to insert it where possible into relatively straight parts of the waveguide run. This minimizes the overall installed loss and permits considerable latitude in following natural terrain features. Sections of 9-m (~30 ft) long helix guide inserted at about 800-m (0.5 mile) intervals are adequate to limit the buildup of unwanted mode levels. The choice of a mode filter spacing of approximately 800 m was aided by a Monte Carlo computer program which simulated the effects of first-order mode conversion losses on the received signal. The simulation showed only modest sensitivity to mode filter spacings in the range of 800–1500 meters. Since the helix guide has higher loss than dielectric-lined waveguide, short mode filter spacings lead to higher overall waveguide losses because there is then a greater percentage of helix waveguide in the transmission medium. Excessively long mode filter spacings, though they have low loss, can result in unacceptable delay distortion of the signal. The difference between curves d and e, Fig. 6, shows a typical added loss from helix mode filters for a helix to dielectric-lined guide ratio of approximately 1:100.

IV. ROUTE ENGINEERING

Route selection and engineering for waveguide differs from that for a coaxial cable system in three respects.

(*i*) The mechanical properties of the waveguide and its sheath restrict the permissible bending configuration of this structure. For engineering purposes plan bends can be laid out simply as two straight tangents connected by a circular arc; a method of profiling based on transparent plastic beam-curve overlays has also been developed to assist in the engineering process.

(*ii*) The loss depends on the configuration as well as the length of the medium. Therefore, computer-aided techniques were developed to take into consideration the configuration of the waveguide plan and profile and to determine waveguide loss and, thereby, assist in the siting of repeater stations.

(*iii*) The rights-of-way which are not available for coaxial cable systems but which can be utilized for waveguide include joint routes with high-voltage power lines (because of decoupling from inductive interference) and interstate highways (because of the large repeater spacing and absence of manhole access requirements).

V. INSTALLATION

To achieve minimum costs, the installation method was carefully integrated with the overall system design.[10,11] The sheath [nominal 5½ inch (140 mm) O.D. pipe] is installed first using pipeline technology; there are no special bedding requirements for the trench bottom. Two minor modifications from pipeline practice are: (*i*) changes in plan and profile must be made in such a way that the sheath is not bent beyond the elastic limit; (*ii*) the welds used in joining the pipe are partial penetration welds to prevent protrusions on the inside which might interfere with the insertion process.

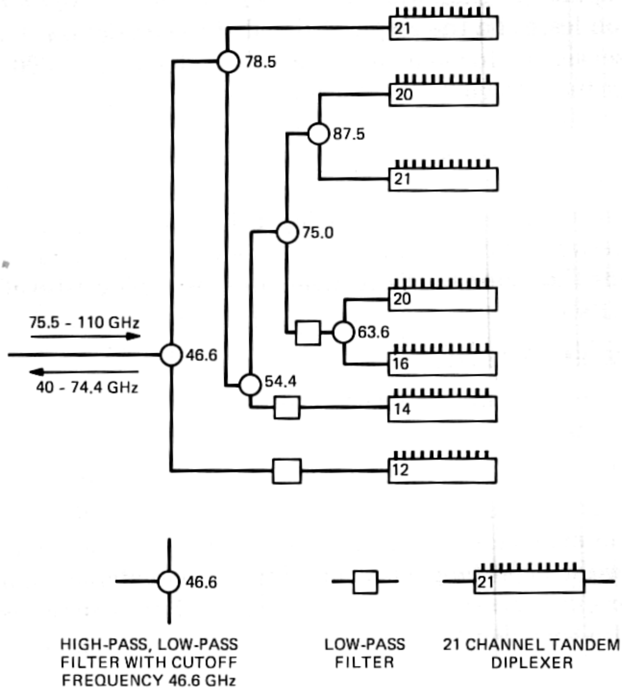

Fig. 7—Multiplexing network plan.

In a second operation the waveguide is installed by field-welding waveguide sections and pushing (inserting) them into the previously installed sheath. The equipment designed to perform the welding and insertion operations requires a five-worker crew and is capable of installing 160 km (100 miles) of waveguide per year with a single-shift operation. Waveguide installation cost (equipment and crew) represents less than 3 percent of the first cost of the system.

VI. MULTIPLEXING NETWORKS

Band diplexers are used to split the overall experimental band from 40 to 110 GHz (38–104.5 GHz commercial) into seven subbands. Tandem-connected channel diplexers consecutively drop or add broadband channels within each subband. Figure 7 shows the actual arrangement of the various filters to give the desired loss shape over the band. The lowest-frequency subband is dropped first and the highest-frequency subband is dropped next. In the lowest-frequency subband, the lowest-frequency broadband channel is dropped first by the string of channel diplexers. In the highest-frequency subband, the highest-frequency broadband channel is dropped first. As shown in Fig. 2, the repeater spacing is maximized by this channelization plan because at frequencies where the waveguide loss is high, the multiplexer loss is low. Further details on the remainder of the Fig. 7 layout are covered by Harkless et al.[12] in a companion paper. The low-pass filters shown are required to control harmonics because the total operating band covers more than one octave.

The band diplexers, high-pass low-pass constant resistance filters, and the low-pass filters are made with circular guide operating in the TE_{01} mode. The input and output ports are 50.8 mm (2 in.) in diameter. The channel diplexers are two-section constant-resistance filters with half-power bandwidths of 475 MHz and center-frequency spacings of 525 MHz (500 MHz commercial). The channel diplexer resonant cavities are in dominant mode rectangular waveguide and are aperture-coupled to semicircular waveguide large enough to support the TE_{01} mode but not large enough to support the TE_{02} mode. These mode restrictions limit the subband bandwidth to about 17 percent. Waveguide tapers and circular-to-semicircular transducers are used as needed between the tandem channel diplexers and the 50.8-mm guide.

The hardware realization of the diplexer components and the four-section modular aluminum frame which supports them and the repeaters is shown in Fig. 8. Modular construction makes the test and installation of the diplexer array very simple. Two frames, each 13 m (43 ft) long, 2.4 m (8 ft) high, and 0.3 m (1 ft) deep, are required at each repeater station. The frame design is controlled mainly by the six individual band diplexers which are about 1.6 m (5 ft, 2 in.) long. The channel diplexers are much smaller; each is about 7.5–10 cm (3–4 in.) long, and 248 are required at each fully equipped repeater station. The frame is very rigid because component alignment is much more important for overmoded waveguide than for dominant-mode waveguide. The band diplexers and low-pass filters are made of aluminum and the channel diplexers are made of high-conductivity copper. Plans to make the critical resonators in the channel diplexers of INVAR to lessen detuning with temperature variations were quickly dropped because tolerances of 2.5 μm (0.1 mil) were required. To meet requirements, temperature control of the multiplexer environment is utilized and the entire multiplexing array is filled with low-pressure dry nitrogen at 180 mm H_2O ($\frac{1}{4}$ psi).

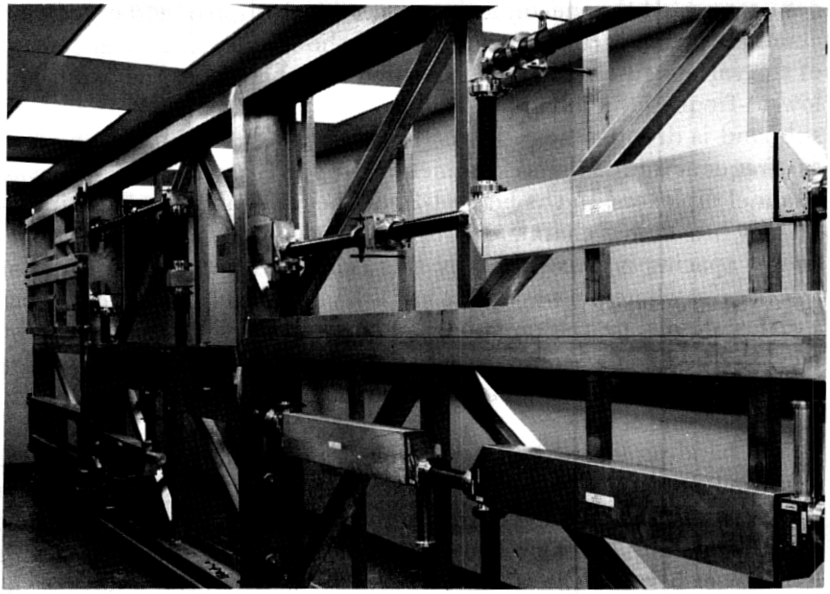

Fig. 8—Diplexer components with four-section aluminum frame.

VII. REGENERATIVE LINE REPEATER

The physical realization of the repeater consists of four units: the transmitter, receiver, power supply and passive line equalizer. A two-level repeater block diagram, without the power supply, is shown in its simplest form in Fig. 9. A CW millimeter-wave signal is generated in the

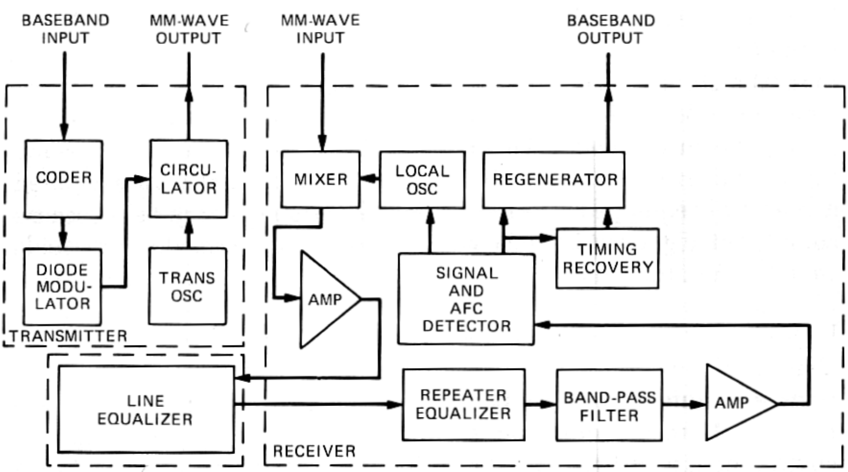

Fig. 9—Repeater block diagram.

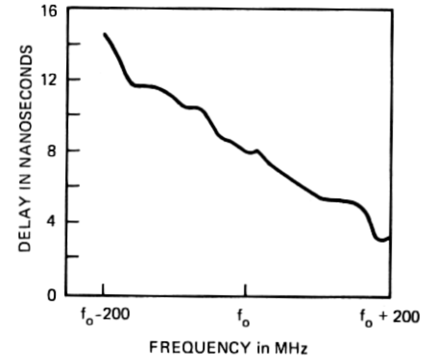

Fig. 10—Typical delay of the line.

transmitter by the silicon IMPATT diode oscillator. The phase modulator, a PIN diode and its associated network, are adjusted so the phase difference between the reflected signals in the conducting and nonconducting states of the diode differ by 180 deg. This phase-modulated millimeter-wave signal is transmitted through the multiplexers and the circular waveguide to the receiver at the next repeater station. At the receiver, the signal is shifted in a mixer, made with a beam-lead GaAs Schottky barrier diode, to an intermediate frequency of 1371 MHz for amplification. The amplified signal goes through the line and repeater equalizers before it undergoes more amplification and is fed into a differential phase detector. The purpose of the line equalizer is to compensate for delay distortion and undesirable loss-frequency shaping caused by the "line." The "line" is defined as the combination of the circular waveguide between repeater stations and the two multiplexing networks between a transmitter and the following associated receiver. The transmission distortion of a particular hop depends on its length and its routing since route curvature affects the characteristics. The dispersion caused by one 60-km hop of 60-mm circular waveguide will introduce as much as 40 ns of almost linear delay across a 400-MHz band. Above about 85 GHz the delay caused by this dispersion is less than 4 ns. The shape of the delay introduced by a typical line will be similar to the curve shown in Fig. 10. The equalizer compensates only for the gross shape shown in Fig. 10; no attempt is made to equalize fine-structure ripple.

The line equalizer is adjusted in the field to compensate for the distortions unique to the specific line and is thereafter associated with the line and is not removed if the transmitter-receiver pair are replaced for any reason. Details of the adjustment of the line equalizer are covered in a companion paper by P. Brostrup-Jensen et al.[13] A line equalizer failure should be a rare event because all its components are passive and experience no dc voltages. In addition to the line, each circuit through which the signal travels introduces some delay distortion and some gain shaping other than that desired. These distortions can cause intersymbol interference. To compensate for these distortions a repeater equalizer is provided which contains delay and loss networks which are adjusted in the factory.

The system was designed so the signal-to-noise ratio at the repeater would assure an error rate better than 10^{-9} even under adverse conditions such as temperature extremes, supply voltage variations, etc. The repeater intermediate frequency is kept fixed through an automatic frequency control circuit, but no control is applied to the transmitter. The transmitter frequency can drift ±25 MHz without causing excessive unequalized delay in the system.

The baseband 274-Mb/s bit stream is scrambled by the nature of the DS4 signal, which uses pseudorandom bit generators located in the time-division multiplexers that feed the WT4 system. The baseband circuits therefore, can be ac-coupled with minimal concern about baseline wander.

Physically the repeater is made in four parts; each part is enclosed in a cast aluminum housing. All parts except the power supply have radio-frequency interference shielding and are pressurized with dry nitrogen to about 180 mm H_2O (¼ psig), available from the waveguide. This controlled atmosphere improves component reliability. All parts of the repeater are flush-mounted on the aluminum frame that also supports the tandem channel diplexers. This type repeater installation is a "plug-in" operation. Some of the channels that make up the frame carry circulating water at about 13°C (55°F). The transmitter and receiver are mounted on these channels, so they are water-cooled. The physical locations of the IMPATT oscillators inside the housings are placed as close to the water-cooled channels as possible. No routine maintenance of the repeaters will be required. At each repeater station there is an error-rate detector which can be connected by command to the output of any repeater at that station. In the event of a repeater failure, the E2A status reporting and control system quickly locates the bad repeater by making use of the error-rate detectors.

Three distinct technologies are required in making repeaters. First, the millimeter-wave parts all use standard rectangular waveguide; three sizes are required to cover the 38 to 104.5 GHz band. Because we operate at such high frequencies, the dimensional tolerances required are stringent. Tolerances of 2.5 μm (0.1 mil) are common and some requirements are even tighter. The mixer uses a beam-lead diode on a gold conductor pattern on a quartz substrate. Second, the IF and most of the baseband circuits are made using hybrid integrated circuits (HIC). The baseband circuits are standard HIC technology but the IF circuitry is more demanding. The line widths in some of the IF networks are 75 ± 6 μm (3 ± 0.15 mils) and line separations must be controlled to ±10 μm (±0.25 mils). Some of the IF circuits require that the dielectric constant of the alumina substrate be held to within ±1 percent of a fixed value. The fixed value itself is not critical, but delay circuits and couplers must be designed for a specific dielectric constant. The third technology is printed circuitry, the least demanding of the three. This technology is used in the AFC and AGC circuits associated with the IF amplifiers, and the power supply circuits.

VIII. PROTECTION SWITCHING

The introduction mentioned that for a fully loaded WT4 system, three broadband channels in each direction are required for protection switching and maintenance. Two of these channels are used for conventional protection switching and the other one is used as a manual patch channel associated with maintenance.[14] Because the waveguide is so much more reliable than any cable,[15] the protection switching signals are sent over waveguide channels. For redundancy, these signals are transmitted over both protection channels. The protection switching signals are digitized and inserted in positions in the DS4 bit stream reserved specifically for auxiliary communications use. These specific time slots are called x-bit slots and the bits are referred to as x-bits. Each x-bit slot has a capacity of 58.3 kb/s and there are three such slots in each DS4 bit stream.

Initially, parity bits are inserted in the DS4 bit stream by M34 time-division multiplex equipment. At the end of each protection switching span there is an error-rate detector called a violation monitor and remover (VMR) which has the following functions. First, it measures the bit error rate by measuring parity in a frame and comparing measured parity with transmitted parity. From this, the error rate for each broadband channel is calculated. Second, the VMR resets the parity bits transmitted to the next switching section so that the next VMR will measure only errors made in its protection switching span.

When the error rate in an east-west broadband channel exceeds 10^{-6}, the VMR in that channel calls for a protection switch. The switch is initiated by signaling the head end of the protection switching span to bridge the bad channel and one of the protection channels. This signaling is sent over the west-east protection channels. When the VMR in the east-west protection channel shows the performance is good, the tail-end switch is executed to complete the protection switching operation. When the VMR in the previously bad channel after repair again shows proper operation, the protection line is automatically switched out and is thus available in case of another channel failure. The actual switching is done with relays that transfer in about 1.5 ms, so a hit or loss of frame results when protection switching occurs. If the switching were associated only with routine testing of broadband channels, loss of frame could be avoided by using fast solid-state switches. However, when there is an unexpected broadband channel failure, the signaling delay caused only by propagation time in a 800-km (500-mile) protection span is enough to cause a loss of frame. Since the WT4 plan does not call for routine testing of broadband channels, switching is done with relays.

In order to extend the repair time available for a failed repeater, one of the three protection channels has been designated a patch channel.[14] It is not part of the automatic protection switching system. It is a fully equipped channel, so by proper baseband patching, any single hop of this channel can be used to replace the hop associated with a failed repeater. Thus, making manual patches at two adjacent repeater stations allows craft personnel ample time to restore the previously bad channel. After this patching, the automatic protection channel is returned to normal operation and is available to protect other failures. Without such a plan, either the time permitted to replace a bad repeater would have to be reduced significantly or at least two more automatic protection channels would be necessary.

IX. ORDER WIRE AND TELEMETRY

Signals associated with the voice order-wire system and the telemetry system are carried in the x-bits transmitted by a specified service channel. The SS3 analog order-wire system and the analog signals associated with the E2A status reporting and control system (telemetry) are put in digital form and multiplexed to form a 58 kb/s signal which in turn is multiplexed with the 274 Mb/s DS4 bit stream. Three adjacent x-bits carry the same information for triple redundancy. Delta modulation is used on the order-wire signals; 29 kb/s is the actual rate needed to carry the signals. The multiplexer which inserts the x-bits into the main bit stream and the associated demultiplexer are hard-wired into the specified service channel so that they are inside the switches in a protection switching span and are not affected by any protection switching operation. How the order wire and telemetry systems function when there is a failure in this specified service channel is covered in a companion paper by Bonomi et al.[14]

The E2A system is modular and can, when properly equipped, provide monitoring of over a thousand points in the WT4 system and can provide momentary grounds for over a thousand points. With proper relays, these grounds provide the command feature for the system. As stated earlier, this system used in conjunction with an error-rate detector at each repeater station can quickly locate a faulty repeater.

X. FIELD EVALUATION TEST

In order to prove in the various manufacturing, installation and service features of the mm-wave transmission system, a field evaluation test was conducted starting in 1974 in northern New Jersey. A 14-km (8.7-mile) waveguide line was installed between the AT&T Metropolitan Junction Station in Netcong and a temporary experimental station in Long Valley. The waveguide was fabricated to manufacturing specifications in an experimental pilot plant at Forsgate, New Jersey, by Western Electric Engineering Research Center and Kearny Works personnel who had developed the manufacturing, test, and inspection techniques in cooperation with Bell Labs.

The terrain used for the 14-km waveguide run offered a variety of construction situations including route bends, road and stream crossings, a steep grade, rocky terrain which required blasting, and swampy areas. The actual sheath installation was done by commercial subcontractors under the direction of AT&T Long Lines Northeastern Area. Long Lines Northeastern Area craft personnel installed the waveguide using tooling and equipment specially developed for waveguide installation by Bell Laboratories and in cooperation with commercial suppliers. Waveguide repair and maintenance procedures were tried out and refined.[15] This demonstrated the viability of the installation and maintenance methods on a commercial basis.

Complete band diplexer modules were installed in both terminal stations but only 12 frequencies in the range from 40–110 GHz were fully equipped with repeaters and channel-dropping networks. The electronics included all elements of the complete operating system such as protection switching, span terminating, fault locating, auxiliary communications, and maintenance.

Twelve repeaters were made by Bell Laboratories to test the system at 12 frequencies in the 40–110 GHz band. The DS4 baseband signal is available at the output of each receiver and tests were made first on the 12 individual hops and then with the 12 connected in tandem. Since the waveguide length used in this test was so much shorter than the proposed spacing of repeaters, it was necessary to use pads to simulate normal repeater operation. By using adjustable pads, the repeaters were tested over a range of input power to the repeaters. These tests showed that the operation in the field was essentially the same as in the laboratory and that the system met all objectives. Periodic tests, however, will be continued to look for changes in line characteristics, receiver sensitivity, frequency stability, etc.

Tests of the protection switching system, electronic fault-locating system, and order-wire circuits showed they met all the design objectives. Experience with measured characteristics of the diplexers and low ad-

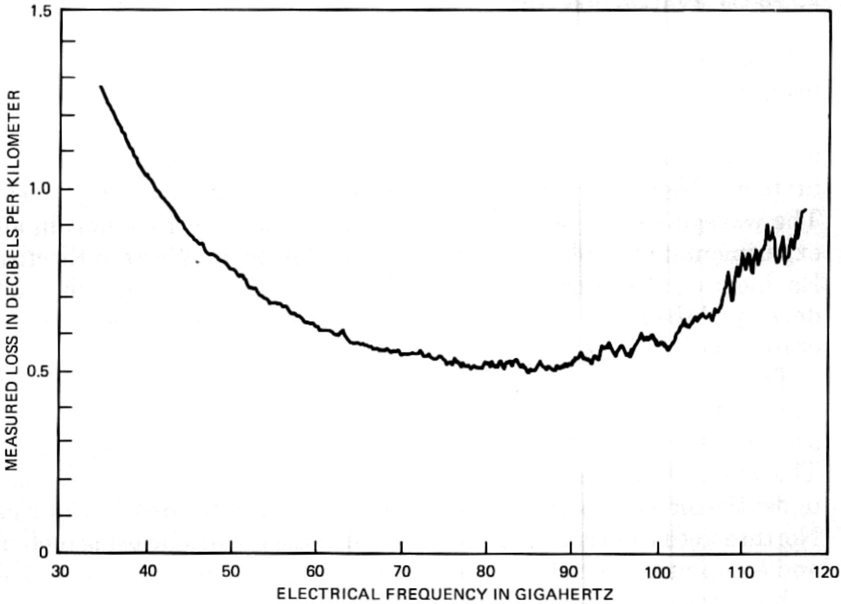

Fig. 11—WT4 field evaluation test measured loss.

jacent-channel interference of repeaters indicated that the guard bands used could be narrowed, permitting a tighter packing of channels.

The results of the measurements on the transmission medium are shown in Fig. 11. The loss of the transmission medium was 1 dB/km or less over the entire frequency band from 40 to 110 GHz. To verify the line behavior outside the operating band, measurements were actually taken from 35 to 117 GHz. The entire line has also been remeasured periodically over the past two years; during this time its loss has remained unchanged within the accuracy of measurement. In addition to overall measurements of the guide, individual sections were measured as they were being installed, both for mechanical distortions of the installed guide and for electrical transmission performance. This permitted refinement and reconciliation of waveguide theory and actual performance.

The calculated 3σ losses for both the moderate-terrain, private ROW route model (south of Washington, D.C.) and the rugged-terrain, private ROW route model (trans-Pennsylvania) are shown on Fig. 12 for comparison. Also shown are the permissible waveguide losses per kilometer for repeaters operating in the 40–110 GHz band over distances of 42 kilometers (26 miles) and 54 kilometers (34 miles) respectively. The difference between these two route models illustrates one of the most important new findings of the test of the transmission medium, namely the sensitivity of loss at the highest frequencies of the WT4/WT4A band

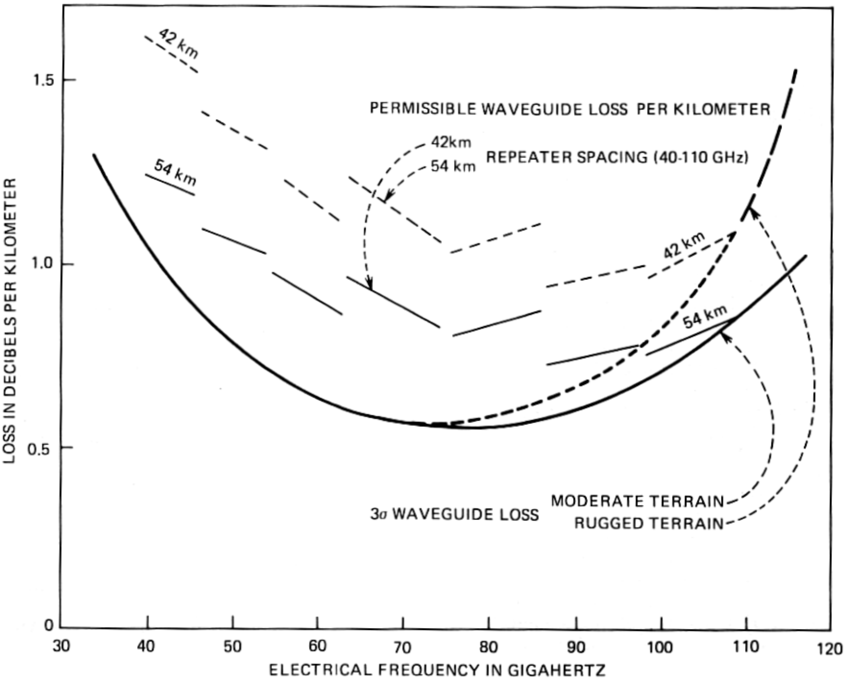

Fig. 12—Waveguide loss and repeater spacing.

to a combination of tight route bends and the natural undulations of the land. This finding was the major stimulus for shifting the frequency band downward to 38 to 104.5 GHz. This downward bandshift also exploits the large margin available at the low-frequency end. A 50 to 60 km repeater spacing can then be attained, rather than a 42 to 54 km repeater spacing corresponding to the 40 to 110 GHz band. This downward shift also includes a slight compression of the guard bands between diplexers and channel-dropping filters as mentioned.

XI. CONCLUSION

The WT4 system provides for economical transmission of a very large communication cross section. Design concepts, manufacturing techniques, and installation methods were proven and demonstrated in a field environment.

XII. ACKNOWLEDGMENTS

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