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WT4 Millimeter Waveguide System:

Field Evaluation Test System Performance

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The WT4 waveguide transmission system is a long-haul digital transmission system operating at 274 Mbaud. Field tests have been carried out on a trial WT4 system including span terminating equipment, repeaters, channelizing networks, and a 14-km waveguide line from Netcong to Long Valley, New Jersey. In this paper the configuration and the principal results of the trial are described. Channelizing networks and repeaters were installed and equalized at 12 different frequencies from 40 to 108 GHz. The principal results include loss and delay measurements of the waveguide and the channelizing networks, and error-rate measurements of two-phase repeaters transmitting 180° phase-shift keyed pulses over the WT4 waveguide line. Extrapolation of the 14-km waveguide loss and the gain and error rate performance of the installed two-phase repeaters indicates that a system with four-phase repeaters operating at the same symbol rate could have spacings as large as 50–60 km.

I. INTRODUCTION

The WT4 waveguide transmission system is a long-haul, high-capacity digital transmission system. The system frequency multiplexes 124 high-frequency carriers into the band 40–110 GHz with each carrier phase-modulated by a 274-Mbaud digital bit stream.[1]

A field evaluation test was carried out in order to obtain a measure of the overall system performance of the WT4 waveguide transmission system. This test included all the elements of a complete operating system such as protection switching, span terminating, fault locating, auxiliary communications, and maintenance, in addition to 12 operating repeaters, channelizing networks, and 14 km of field-installed waveguide.

In this paper the emphasis will be placed on the combined performance of the repeaters, line equalizers, channelizing networks, and the waveguide medium. Companion papers[2–5] discuss the design of each of these individual elements in detail. Similarly, the span terminating, protection switching, auxiliary communications, and maintenance subsystems are discussed in an additional companion paper.[6]

For the field evaluation test, 14 km of waveguide was installed from a metropolitan junction station at Netcong, New Jersey, to a temporary equipment shelter at Long Valley, New Jersey. At each end of the waveguide a complete band diplexer array was installed along with enough channel diplexers to allow the testing of the 12 repeaters that were built for the field evaluation test.* The repeaters were divided into four groups, each of three repeaters centered near 40, 55, 80, and 110 GHz. Since six of the repeaters operate below 75 GHz and transmit in one direction while the other six transmit in the opposite direction, this arrangement could be used to connect up to 12 repeaters in tandem by looping back at baseband. The repeater frequencies were carefully chosen so that adjacent channel interference and interferences from harmonically related frequencies could be evaluated; for example, 40-GHz repeaters interfering with 80-GHz repeaters. Because the waveguide run is short, attenuation was provided in the rectangular waveguide portion of the system to adjust the power levels to approximate the loss of 40 km or more of waveguide. This loss was provided in the form of both fixed and variable attenuators and could be placed at either the transmitting or receiving end or could be divided between them.

The main objective of the tests was to measure repeater performance in the field where we would encounter degradations due to transmission deficiencies of the line (the waveguide and the channelizing networks), misequalization, interchannel interference, interactions between the repeaters and the channelizing networks, baseline wander and bit timing recovery phase jitter. The results of the tests were then used to predict system performance and repeater spacing for an advanced system using four-phase repeaters. The repeaters used in the test were two-phase repeaters using a differentially coherent phase shift keying (DCPSK) digital modulation scheme to transmit 274 Mb/s. The advanced four-phase repeater would use a coherent PSK scheme to transmit 548 Mb/s.

II. CHANNELIZING NETWORK

The array of filters to be used to connect individual channels to the

* For a detailed discussion of the millimeter-wave channel diplexers, band diplexers, and channelizing network, the reader is directed to Reference 4.

Table I — Midband insertion loss for channelizing networks

Frequency, GHz	Insertion loss: Netcong, dB	Insertion loss: Long Valley dB
40.235	3.4	3.5
40.760	3.6	3.6
41.285	3.6	3.6
53.910	5.3	5.7
55.085	9.4	9.8
55.610	9.5	9.4
80.465	8.2	8.8
80.990	8.0	9.0
81.515	8.2	8.8
107.665	5.9	6.4
108.190	6.0	6.4
108.715	5.3	5.1

waveguide medium has been described in Ref. 4. Two complete band-splitting filter arrays were constructed and installed at Netcong and Long Valley. Five of the seven subbands at each location were partially equipped with channel-dropping filters; i.e., filters for all 12 field evaluation test frequencies were installed at both ends and in addition, Long Valley had six additional filters in the 80-GHz subband for a total of nine channel filters connected in tandem. The insertion loss and differential delay were measured from the circular waveguide connection port to each of the 12 or 18 rectangular waveguide connection ports. The circular waveguide medium is connected to the circular port and the repeaters are connected to the rectangular ports. Each of these loss measurements was compared with the sum of the individual filter losses which had been previously measured in the laboratory. The average disagreement between measurement of the assembly and the sum of the pieces was 0.2 dB. The worst interaction between filters occurred in the subband near 55 GHz where return loss and mode conversion echoes created fast transmission ripples. Table I gives the midband insertion loss measured for each of the field evaluation test channels at Netcong and Long Valley. It is seen that the lowest-frequency channel has a channelizing network loss of about 3.5 dB and the highest frequency about 5.2 dB. These values correspond to the system objective of obtaining lowest channelizing-network loss at the lowest frequency and fairly low loss at the highest frequency so as to complement the loss shape of the medium.

III. LINE EQUALIZATION

The equipment and techniques for equalization of the field evaluation test system are described in a companion article.[3] Each transmitter-receiver pair, connected back-to-back through a flat precision attenuator, was measured first in the laboratory and then again at intervals of several months, after shipment to the field. The largest changes ever observed

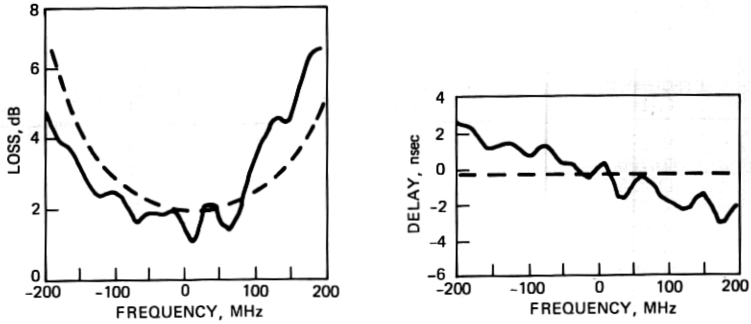

Fig. 1—Unequalized loss and delay characteristics.

in the back-to-back response were ±0.2 dB and ±0.2 ns with typical changes being ±0.1 dB and ±0.1 ns, which compares favorably with the measurement accuracy of ±0.1 dB and ±0.1 ns.

The characteristic of a line is the difference between the back-to-back response and the response with the channelizing networks and waveguide inserted between the transmitter and the receiver. Since all measurements are stored on tapes in the test set, differences are immediately available. A comparison with the desired optimum response for the channel established the required equalizer shape. Equalizers with the appropriate shape were laser-trimmed and assembled typically within one week by using a synthesis program available at Bell Labs, Holmdel.

Figure 1 shows the measured characteristics of a channel in the 80-GHz subband (solid curve) and the desired characteristics (dashed curve). The fast ripples in the transfer function are due mainly to the channelizing filters; the waveguide medium contributes negligibly to the ripples. The results of equalization are shown in Fig. 2. Note that the peak-to-peak variations in amplitude and delay after equalization are about ±0.5 dB and ±1.0 ns and that the line equalizer has removed all of the slowly varying distortion. This amount of residual variation is well within our conservative allocation of up to ±2.5 dB and ±2.7 nsec.

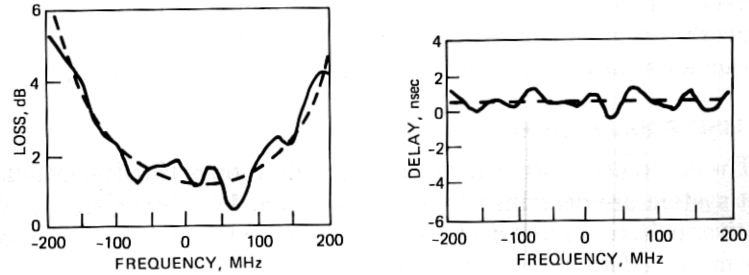

Fig. 2—Equalized loss and delay characteristics.

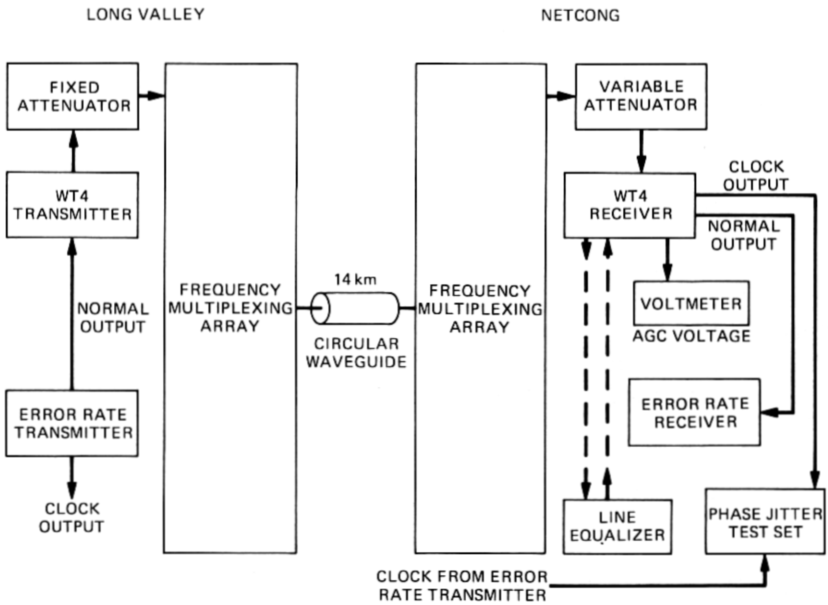

Fig. 3—Equipment arrangement for field measurements.

The line equalizer is a separate unit. It is unique to the particular location and particular line and is independent of the transmitter-receiver pair. Since the equalizer package is passive, it is not prone to fail; should it fail, a duplicate can be made based on the original test data. Therefore, the equalization test set is needed only during initial installation; it is not required as part of any maintenance and repair procedure.

IV. ERROR RATE MEASUREMENTS

Since the WT4 system is a digital transmission system, the degradation that it introduces becomes apparent in the form of bit errors. An error-rate measurement is, therefore, an overall measure of system performance and is of paramount importance. For this reason, error rate measurements were made for a number of different system configurations using an error-rate test set. A typical arrangement is shown in Fig. 3. At the transmitter the error-rate test set can generate a pseudorandom pulse sequence of either length $(2^{11}-1)$ or $(2^{15}-1)$ and at the receiver the test set can synchronize to either of these signals and detect any line errors. With sequences of these lengths we can measure the effects of intersymbol interference spread over as much as five to seven time slots. The fixed attenuator after the transmitter and the variable attenuator ahead of the receiver provided a means of varying the received power so that error rate versus received power or versus signal-to-noise ratio could be measured. As indicated by the dashed line, the performance with or without the line equalizer could be measured.

Other arrangements were to measure the error-rate performance of one channel while sending data over an adjacent channel or a harmonically related channel to determine the amount of adjacent and interchannel interference. Tests were also run with repeaters connected in tandem to insure that electrical interfaces had been satisfactorily engineered.

An error-rate objective of 10^{-9} or less per repeater hop was set to insure that a long-haul system encompassing as many as 200 repeaters would have a very small probability of having an error rate which exceeded 10^{-6}, 10^{-6} being the long-haul error rate objective.

From these measurements the available gain of the repeater (G_A) and the required relative carrier power (RCP) for an error rate of 10^{-9} could be determined. G_A is an overall measurement of the repeater performance and is given by

$$G_A = P_T - P_R \quad \text{dB}$$

where P_T is the output power of the transmiter and P_R is the minimum receiver input power in dBm for an error rate of 10^{-9}. That is, G_A is the maximum attenuation that can be placed between the transmitter and the receiver and still have the repeater operate at an acceptable error rate. Since G_A is defined in this manner it inherently encompasses all sources of degradation and all noise contributions and is the single most important measure of repeater performance. G_A is defined for each broadband channel and is, therefore, a function of frequency.

The minimum receiver input power P_R for a 10^{-9} error rate can be written in a simplified manner as

$$P_R = N_T + \text{NF} + \text{RCP} \quad \text{dBm}$$

where N_T is the thermal noise, at room temperature, in a bandwidth equal to the signaling rate of 274.176 Mbaud and NF is the noise figure of the receiver. RCP, the relative carrier power, is a comparative measure of how large the carrier power must be relative to the actual noise level in the signaling rate bandwidth, so that the repeater will operate at an error rate of 10^{-9}.

RCP is made up of two parts. The first part, "theoretical minimum," is the RCP that would be required for an optimum transmission and detection scheme. The second part, known as the "degradation," is the additional power that is required because none of the system elements, such as the transmitter, channelizing networks, waveguide medium, or receiver are ideal.

Table II is a summary of our measurements of required RCP. There are three sets of measurements: (*i*) back-to-back in the laboratory, (*ii*)

Table II — Relative carrier power measurements

Frequency, GHz	Back-to-back, dB	Line unequalized, dB	ΔRCP, dB	Line equalized, dB	ΔRCP, dB	Objective, dB	RCP margin, dB
40.235	15.8	—	—	17.4	1.6	22	4.6
40.760	14.7	—	—	16.8	2.1	22	5.2
41.285	15.1	—	—	16.1	1.0	22	5.9
53.910	15.6	17.6	2.0	16.4	0.8	22	5.6
55.085	15.4	20.2	4.8	18.3	2.9	22	3.7
55.610	14.7	19.7	5.0	18.2	3.5	22	3.8
80.465	16.0	17.8	1.8	17.9	1.9	22	4.1
80.990	14.6	17.0	2.4	16.9	2.3	22	5.1
81.515	15.7	16.4	0.7	17.1	1.4	22	4.9
107.665	14.6	16.7	2.1	17.1	2.5	22	4.9
108.190	15.8	18.7	2.9	18.5	2.7	22	3.5
108.715	15.3	16.9	1.6	16.9	1.6	22	5.1

over the line without equalization, and (*iii*) over the line with equalization. The ΔRCP columns are the increases in RCP above the laboratory back-to-back measurements. For the lowest frequency channels there are no "unequalized" measurements because the large amount of linear delay distortion at these low frequencies precluded error rate measurements without equalization. Note that the average RCP in the back-to-back mode is about 15.2 dB which is 2.2 dB above the theoretical minimum for DCPSK of 13.0 dB at an error rate of 10^{-9}. After equalization, the average RCP is 17.3 dB for an average penalty of 2.1 dB above back-to-back. Furthermore, even the worst channel (18.5 dB) is well below our system design objective of 22 dB. Note that the line equalizer is most effective for low frequencies where there is a large amount of linear delay distortion and becomes less effective as the frequency increases.

In a similar manner, Table III presents results of the error rate measurements in terms of available gain. Here we show the transmitter power (P_T) and the minimum receiver power (P_R) for 10^{-9} error rate. The available gain is G_A. Note that in only one case, 107.665 GHz, are we below our objective, and then only by 0.1 dB. This was due to higher-than-expected loss in both the mixer and the phase shift modulator. Note in general that we tend to have more margin at the lower frequencies due to better mixer and phase shift modulator performance.

V. LEAKAGE AND INTERFERENCE

With 62 transmitters and 62 receivers connected to each end of every transmission span, there are many opportunities for leakage and interference. The millimeter-wave channelizing filter two-pole response is such that the adjacent channel leakage is only 14 dB down at the center of the pass band. However, several field evaluation tests have shown no

Table III — Available gain measurements

Frequency, GHz	P_T, dBm	P_R, dBm	G_A measured, dB	G_A objective, dB	G_A margin, dB
40.235	19.5	−59.1	78.6	72.6	6.0
40.760	19.9	−60.4	80.3	72.6	7.7
41.285	19.3	−59.3	78.6	72.6	6.0
53.910	17.2	−56.8	74.0	69.7	4.3
55.085	17.4	−54.5	71.9	69.5	2.4
55.610	16.9	−58.4	75.3	69.5	5.8
80.465	13.7	−54.0	67.7	65.2	2.5
80.990	13.1	−53.7	66.8	65.2	1.6
81.515	13.6	−56.2	69.8	65.2	4.6
107.665	10.3	−51.0	61.3	61.4	−0.1
108.190	11.0	−52.4	63.4	61.4	2.0
108.715	9.7	−54.9	64.6	61.4	3.2

P_T = transmitter power, dBm
P_R = received power for 10^{-9} error rate, dBm
G_A = available gain, dB
$G_A = P_T - P_R$

measurable degradation due to the presence of an adjacent channel signal. It is expected that a change to four-phase modulation will result in only a small (less than 0.1 dB) increase in this degradation. Attempts have been made to measure second harmonic output from field evaluation test transmitters, but no energy has been detected with systems capable of measuring to −65 dBm. Similarly, the field evaluation tests have shown no measurable second harmonics. A series of nine different field tests looking for image response and receiver response to the local oscillator second harmonic has yielded only one detectable interfering tone and no measurable degradations of the system response at a 10^{-9} error rate.

VI. BASELINE WANDER AND TIMING RECOVERY PHASE JITTER

The investigation of two phenomena, baseline wander and timing recovery phase jitter, required a slight modification of the test setup as shown in Fig. 3. Baseline wander is a term used to describe the degrading effect of removing the low-frequency portion of the baseband signal by utilizing ac coupling in the regenerator, a technique which greatly simplifies the circuit design. The ac coupling used had a 3-dB cutoff frequency of about 10 kHz and since a pseudorandom sequence of length equal to $2^{15}-1$ at a signaling rate of 274 Mbaud has frequency components spaced every 8.4 kHz, a longer sequence was required to measure the degrading effects. Similarly, the closed loop bandwidth of the timing recovering phase-locked loop is also about 10 kHz and, therefore, again required a longer sequence in order to test the degrading effects of bit timing recovery phase jitter. A longer sequence was generated by cascading two pseudorandom word generators, one of length $2^{11}-1$, and the other of length $2^{15}-1$ to form a word of length $(2^{15}-1)(2^{11}-1)$ which is approximately 2^{26} and which has frequency components spaced every 4.1 Hz. Error rate measurements using first the short sequence $(2^{15}-1)$ and later the long sequence (2^{26}) indicated that neither baseline wander nor phase jitter introduced any measurable degradation (less than 0.1 dB). Using the long sequence, the measured rms phase jitter was about 0.5 deg for a single repeater and was about 1.4 deg for a cascade of 10 repeaters. The phase jitter was measured by comparing the relative phase of the clock output of a repeater and a highly stable reference clock in the error rate transmitter. This phase jitter performance was very close to what was anticipated and an extrapolation of this data indicates that for a complete system of about 200 repeaters the rms phase jitter should be less than 10°. This is quite acceptable considering the fact that the digital multiplexers can easily handle phase jitter in excess of several hundred degrees.

VII. SUMMARY

In determining overall system performance, the available gain, G_A, of the repeater, both in the laboratory and again in the field after installing the repeater, has been measured. Also, the relative carrier power RCP (an important component in determining available gain) has been measured under both conditions. The relative carrier power and, of course, the available gain is a function of the measurement conditions; i.e., if interfering tones or distortions of the transfer function shape are present, then greater RCP is required to attain the error-rate objective. Table II shows the measured RCP for the two conditions. The required RCP for a 10^{-9} error rate changed from about 15 dB to 18 dB primarily due to distortion in the transfer function shape introduced by the channelizing networks and the transmission medium. The available gain would, of course, be correspondingly reduced by 3 dB.

In order to understand the significance of the measured available gain of the repeater and the loss of the waveguide medium, we can make the following calculation. At 40 GHz, 78 dB of available repeater gain was measured in the laboratory. When the repeater was installed in the field, there was a 2-dB reduction in available gain. Furthermore, when the repeater was installed in the field, the RCP was about 17 dB. In our system design we have assumed an RCP of 22 dB, which means a safety margin of 5 dB above the measured value of 17 dB. This is more than sufficient to take care of aging and additional interference that might occur when all 124 channels are operating. Therefore, the available gain that we should use for an installed two-phase repeater at 40 GHz is 71 dB. This was arrived at by taking the laboratory measurement of 78 dB and subtracting the 2-dB reduction actually observed in field installation and also subtracting the additional margin of 5 dB.

This available gain must overcome the loss of the channelizing networks at each end, the loss of the waveguide medium, and the additional loss that might be incurred during a waveguide repair. At 40 GHz the loss of the channelizing networks is 7 dB and we have allowed 3 dB of additional loss during the time the waveguide medium is being repaired if it has been damaged and for route rearrangements.[8] These two components sum to 10 dB and when subtracted from the available gain of 71 dB mean that 61 dB of loss is allowed for the medium at 40 GHz. The medium loss as measured is 1.0 dB/km at 40 GHz.[7] Therefore, 61 dB of loss is equivalent to a repeater spacing of 61 km. A similar calculation at 109 GHz yields a 62-km repeater spacing. Thus, we can conclude that the field evaluation test system performance is more than adequate to insure very large (in excess of 60 km) two-phase repeater spacing.

For future development of a commercial four-phase system, as discussed in Alsberg et al.,[1] the operating frequency band is being shifted to 38–104.5 GHz. Laboratory tests of improved repeater circuitry indicate that available gains ranging from 75 dB at 38 GHz to 59 dB at 104.5 GHz can be expected. This estimate of four-phase repeater available gain means that we could expect a four-phase system to have a repeater spacing of 50–60 km.

VIII. ACKNOWLEDGMENTS

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