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DIGITAL MICROWAVE RADIO APPLICATIONS IN ELECTRICAL POWER SYSTEMS

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FOREWORD

The application of Digital Microwave Radio to Electrical Power Systems appears to be growing at an accelerated rate. Electric utility managers and their electronics and communications engineers have been concerned about the question of when to start applying Digital Microwave ever since it was presented as a marketable new technology over ten years ago. Engineers given the responsibility of designing microwave radio systems for electrical utilities have been handicapped in not having available in one document a report on Digital Microwave Radio Applications which would (a) introduce the subject of digital microwave in the form of a tutorial and (b) list some of the existing applications in the area of communications, measurement and control in electrical substations. We hope that this report will serve that need.

This report was prepared by the Microwave and Radio Subcommittee of the Power System Communications Committee (PSCC) of the IEEE Power Engineering Society.

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The PSCC Chairman wishes to acknowledge the contribution of Dr. K. Feher in helping to develop the tutorial section of this paper.

DIGITAL MICROWAVE RADIO APPLICATIONS

IN ELECTRICAL POWER SYSTEMS

PSCC Microwave & Radio Subcommittee Working Group Report

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DIGITAL MICROWAVE RADIO APPLICATIONS IN ELECTRICAL POWER SYSTEMS

PSCC Microwave & Radio Subcommittee Working Group Report

ABSTRACT/SCOPE

This guide provides the reader with a tutorial in Digital Microwave Radio theory and design, applications to the electrical power industry, guidelines in the selection of Digital Microwave Radio Systems, sample specifications, and references including technical papers, books, and magazines.

INTRODUCTION

Electronics and communications engineers working for electrical utilities have been concerned about the question of when to start applying Digital Microwave for over ten years. They have been concerned about applications to meet the control, protection, and administrative data needs of their utility ever since the first Digital Microwave System was made available on a commercial basis in the early 1970's. The Microwave & Radio Subcommittee (M&RS) of the Power System Communications Committee (PSCC) decided to take advantage of the fact that its members represent Electrical Utilities in Canada, Mexico and the USA, which could provide a good cross-section of the engineering concerns and could gather the necessary information in one document to respond to those concerns. This guide is the result of their efforts.

TUTORIAL ON DIGITAL MICROWAVE RADIO SYSTEMS

Historical Remarks

Microwave systems had their beginning in 1933, when a group of British and French engineers installed a 1750 MHz system across the strait of Dover. However, it was not until the late 1940's and early 50's that microwave systems achieved commercial acceptance.

In the past three decades of commercial use, microwave system technology has evolved into higher capacity, lower power drain, smaller size, higher reliability products. A major driving force in this technological evaluation is the never ending search for better frequency spectrum utilization.

In the past ten years the microwave technological development has moved at an accelerated rate in the direction of digital RF carriers utilizing Phase Shift Keying (PSK), AM, FSK, etc.,. Also, progress of electronics technology, especially semiconductor technology, is impressive. Large Scale Integration (LSI) on silicon chips of digital and analog circuits have become available.

The use of LSI and hybrid IC's provides the following exceptional advantages:

- o Greater compactness
- o Lower power consumption
- o Increased reliability
- o Modularity
- o Flexibility
- o Quality Assurance
- o Functional over a wide range of ambient conditions
- o Economization

Development of new technology has again advanced the telecommunications industry to the edge of new thresholds which cause questions by the users as to whether the analog microwave systems will be replaced by digital microwave systems and if so, when?

The primary impetus for considering digital systems is related to the economics brought about by increased digital communications channel/circuit requirements. For medium to heavy density systems with few backbone RF repeaters, digital multiplex equipment is less expensive than analog multiplex equipment. In addition, there are perceived advantages of digital microwave in low density, long distance digital channel applications as well as in the higher density applications. One example is the inherent ability of digital microwave RF to maintain its audio Signal-to-Noise ratio at "no fade" all the way to RF receiver drop out with little degradation since the "fade" noise is primarily amplitude oriented.

The time division multiplexer (TDM), perhaps even more than advanced transmission devices such as digital radio and fiber optics, is responsible for the rapid growth of digital telecommunications. Digital radios, generally speaking are more expensive than analog radios, largely because of greater complexity and hitless switching protection requirements. This is usually more than offset by the cost savings realized by using digital multiplexers

Multiplex cost, of course, becomes the predominant factor in overall system cost calculations as the number of channels required continues to increase.

The rapid advances in digital technology during the past ten years has spurred development of higher capacity digital systems utilizing higher order modulation techniques which result in more efficient systems.

Digital Technology

The primary objective of every microwave radio communication system is to transmit intelligence from one point to another without distortion or other transmission impairments, such as the addition of extraneous signals. The transmission facility could carry speech or music, printed text or pictures, high speed data, facsimile, etc. In all cases the ideal transmission facility should be 100% reliable which, although impossible to meet in practice, is closely approximated by proper systems design and judicious system engineering. It is necessary to consider the significant factors which affect transmission. A proper balance must be maintained between performance and cost.

The noise performance of a system is one of the most important parameters with significant effects on many phases of equipment and system design. The total noise results from divergent sources, including thermal, intermodulation, echo path distortion, interference (RF and EMI), and in some instances harmonics caused by amplifier non-linearities.

Digital modulation is relatively insensitive to noise interference and to phase and amplitude distortion. The system characteristics for digital transmission of high bit rates requires attention to the following:

- o Choice of the RF band and use of the spectrum
- o Coexistence with SSB/FDM systems
- o Choice of the modulation type
- o Definition of the system performance and the electrical characteristics of each functional block

In digital modulation techniques, the efficient use of the spectrum, which is always an important consideration, depends primarily on the type of modulation selected. When the various types of modulation are compared, the most significant parameters are found to be the following:

- o Bandwidth occupied
- o Signal-to-Noise ratio at the input of the receiver for a given error probability
- o Complexity of circuits
- o Tolerance to distortion and interference

Table I lists most of the currently used digital modulation techniques and indicates the ratio of average signal energy per bit to noise power spectral density measured at the receiver input E_b/N_o. The quantity E_b/N_o is a figure of merit which is derived from Shannon's theory. The most meaningful measure of performance in a digital system is the Bit Error Rate (BER) at the receiver digital multiplexer output. Table I figure of merits are based on a BER of 10^{-6}.

TYPE	MODULATION SCHEME	SPEED BER OF 10^{-6} b/s/Hz	$\frac{E_b}{N_o}$ (db) (IDEAL)	$\frac{E_b}{N_o}$ (db) (FINITE BANDWIDTH)
AM	OOK-COHERENT DETECTION	0.8	11.4	12.5
	OOK-ENVELOPE DETECTION		11.9	
	QAM	1.7	8.4	9.5
	QPR	2.25	10.7	11.7
FM	FSK-NON COHERENT DETECTION	0.8	12.5	11.8
	CF-FSK COHERENT DETECTION		7.4	
	CP-FSK NON COHERENT DETECTION	1.0	9.2	10.7
	MSK	1.9	6.4	9.4
	MSK-DIFFERENTIAL ENCODING	1.9	9.4	10.4
FM	BPSK-COHERENT DETECTION	0.8	8.4	9.4
	DE-BPSK	0.8	8.9	9.9
	DPSK	0.8	9.3	10.6
	QPSK	1.9	8.4	9.9
	DQPSK	1.8	10.7	11.8
	OK-QPSK		8.4	
	8-ARY PSK-COHERENT DETECTION	2.6	11.8	12.8
	16-ARY ARY PSK-COHERENT DETECTION	2.9	16.2	17.2
AM/PM	16-ARY APK	3.1	12.4	13.4

TABLE I. - RELATIVE SIGNALING SPEEDS OF REPRESENTATIVE MODULATION SCHEMES.

Pressure to increase the channel capacity of digital systems to match or exceed the capacity of analog systems in a given bandwidth will undoubtedly lead to more complex digital modulation schemes and in turn, more complex equalization and protection methods.

In comparison to digital transmission, the term "voice band data" is used to describe the transmission of digital information over the voice telephone network. Data transmission is accomplished by external devices called modems, which transform digital information into analog signals suitable for transmission over the network.

Digital radio refers to the transmission of digital information over microwave radio channels at frequencies from 2GHz to 20GHz. Digital radio systems have been used primarily to provide trunks, or transmission channels between switching centers in the telephone networks. Typical systems provide several hundred to more than a thousand trunks on a single RF channel. Analog-to-digital conversion is used to convert the analog voice signals to 64 kilo bits per second (kbps) streams prior to radio transmission. This conversion is normally done by digital channel banks external to the digital radio system, or by the switching systems themselves.

The demand has been increasing recently for long-haul digital networks to transmit data, facsimile, etc. signals. In order to meet this demand economically in a short time period, DUV (data under voice), DIV (data in voice), and DAV (data above voice) have been developed. These techniques make use of existing FDM systems for long-haul transmission by bandwidth compression methods of converting digital signals into multilevel PAM (pulse amplitude modulation).

DUV/DIV/DAV systems have the following features:

(1) Low cost, long haul digital transmission using existing FDM systems

(2) High efficiency transmission of 3.2bps/Hz to 5.1bps/Hz

(3) High transmission quality with Bit Error Rates less than 10^{-8} and 10^{-9}

In addition several new fundamental technologies have been developed:

(1) The adaptive equalizing method provides excellent converging properties for the highly dispersive channel.

(2) The automatic phase control method provides accurate phase synchronization.

(3) The in-band and in-phase pilot coupling method provides very effective use of frequency band and suppression of phase jitter.

(4) Master Group (MG) Automatic Gain Control (AGC) and MG pilot canceller, using phase locked loop (PLL), which are compatible with the existing MG AGC.

(5) Forward error correction techniques which can be applied to systems with severe Signal-to-Noise (S/N) conditions.

Digital switch installations with their attractive features of smaller size, lower cost, and trouble diagnostics built-in to aid maintenance have virtually eliminated analog switches as a consideration for new installations. The popularity of this digital switching technology makes it more desirable in many cases to provide a digital microwave system with its DS-1 compatible interface in place of the analog microwave system with its analog-to-digital converter.

Data transmission provides another example of digital microwave networks. In current digital microwave multiplex designs the voice channel modem can be removed and replaced with a data channel modem having a capacity of up to 56kbps. Analog digital data counterparts normally require a group bank modem displacing the equivalent of 12 voice-grade circuits.

Another consideration is that an analog voice channel used for data transmission usually requires a 4-wire voice channel with good equalization and the cost of a separate data modem in order to carry data at speeds up to 9600 bps.

Digital microwave systems are available in the industrial fixed, common carrier, and government bands of 1.7/2, 6/7/8, and 11/12/15 GHz. Even though at first glance the digital microwave might appear to be less efficient in total capacity compared to the latest analog counterparts, it is well to remember that each of the 1344 audio equivalent digital channels can handle as much data as 12 channels in the analog microwave world.

To many the opportunity to supply the digital needs for the "Office of the future" makes the digital network concept the most attractive choice. However, for the majority of Electric Utilities, office networks may not be the determining factor since the justification for most Electric Utility oriented microwave systems is to provide power system control functions (relaying, control, data, etc.,) with administrative data second in importance. Thus the determining factor may be the lower cost of analog long haul microwave systems with economical low density drop out channels at mountain top locations (for mobile radio base stations, hydrometeorological facilities, etc.).

Digital microwave transmission did not always enjoy the advantages listed today. Early digital systems did not degrade gracefully like their analog counterparts. On some occasions radio propagation failed for no apparent reason. Pseudo-error monitors could not pinpoint the problems, making performance monitoring costly and time consuming.

Today, versatile microprocessors have become available and are incorporated in current designs to perform diverse functions as controlled by custom software.

Older digital microwave designs monitored performance with intentionally degraded detectors which employed offset slicers or timing. This permitted an approximate measure of the bit error rate (BER) and was used to initiate transfer from the primary path or channel to the standby channel before the actual loss of data occurred on the primary channel.

It may be important to realize what is actually transmitted when comparing FDM (Frequency Division Multiplex) to TDM (Time Division Multiplex). The FDM unit transmits the actual analog input as modulation on a carrier, whereas a TDM device digitally encodes the analog signal and transmits digital information representing the analog signal. In other words, FDM equipment transmits a signal whereas a TDM unit transmits information. At the receiving end of the FDM system the carrier is simply removed, yielding the analog signal; in comparison, the TDM unit receives the digital representation of the analog signal and from this information regenerates the analog signal.

The Signal-to-Noise ratio (SNR) is reflected in the digital system as BER. The digital system is characterized as being relatively immune to Signal-to-Noise degradations in the system until it approaches the noise threshold where it will degrade at an accelerating rate ("crashes"). When the SNR in the digital system reaches threshold, the BER "crashes" within 3 to 4 dB. Until threshold is reached, however, the digital signal can be regenerated at a number of hops to eliminate the build-up of noise as experienced by analog systems. Refer to Fig. 22, page 28.

The TDM multiplexer/channel bank accepts either digital or analog input signals and produces a single digital bit stream output. Analog signals are digitally encoded such that the actual multiplexing operation involves only digital signals. Each digital signal is sampled at some fraction of the multiplexer's output data stream rate and is assigned a time slot in the output data stream to produce a continuous digital signal or bit stream. This entire composite bit stream can be applied to a digital encryption unit and scrambled as a bulk signal without the introduction of distortion.

The digital encryption process has advantages over the FDM unit since the FDM multiplexer requires 24 separate encryption units compared to only one for the TDM device. Also, TDM encryption is simpler and more effective.

Modulation Methods and Applications

A digital modulation scheme modulates a carrier so that the signal is keyed from its previous state to one of a finite number of possible states. These states may be in amplitude (ASK, Amplitude Shift Keying), frequency (FSK, Frequency Shift Keying), phase (PSK Phase Shift Keying), or some combination, for example, QAM (Quadrature-Amplitude Modulation). In these modulation methods PSK has been preferred to FSK or ASK up to now because the required SNR for FSK or ASK is 5 to 10 dB higher than that for PSK for the same spectrum utilization efficiency factor. When PSK is compared to QAM for the same spectrum utilization efficiency, the QAM is better than the PSK. For example, 16 QAM with a 0.5 roll-off factor (requiring a 21 dB average SNR with a 10^{-6} BER can achieve an efficiency of higher than 2.5 bits/s/Hz or 5 bits/s/Hz if dual polarization transmission is used. This efficiency of 5 bits/s/Hz, which is equivalent to 72 voice circuits/MHz, is considered to be about the same efficiency as an FM analog system of 90 voice circuits/MHz.

The larger the modulation level number is, the higher the spectrum utilization becomes. However, it is very difficult to realize the 64 or more multilevel-QAM system for the following reasons:

1. A received signal spectrum resulting from a multipath fading channel is strongly dispersed within the band. At the same time, the permissible in-band dispersion becomes so small that the system would not operate satisfactorily during fading periods, even if space diversity and an adaptive equalizer could be used.

2. Such a system becomes more sensitive to interference. Consequently, the utilization of dual polarized waves would be difficult and thus would lead to a decrease in spectrum utilization efficiency.

3. The equipment fabrication feasibility factor would be less since it would be difficult to design a model which would satisfy the requirement for a recovered-carrier SNR greater than 40dB with a very small modulation phase error.

Multipath propagation conditions produce frequency-selective distortions in the radio channel whose adverse effects depend on the nature of the transmitted signal. A frequency-selective fading occurrence that would only increase the noise in FDM/FM transmission causes interruption of a 16-QAM digital transmission unless appropriate countermeasures are taken. These include adaptive equalizers and diversity reception. A single selective fading countermeasure may be sufficient in many applications with moderate RF channel distortion, whereas the more unfavorable multipath propagation conditions may require the combined use of two or three countermeasures.

Figure 1 shows the "State-of-the-art" Digital Microwave Radio Systems which have been manufactured throughout the world. In Japan, the short-haul digital radio system (2 GHz, 16 Mbits/s) in 1969 and the long-haul, high-capacity system (20 GHz, 400 Mbits/s) in 1976, were developed as the first commercialized systems in the world. As of early 1981 the average Spectrum Utilization Efficiency of commercialized systems was less than 3 bits/s/Hz and had bit rates less than 100 Mbits/s. Since 1981, 16- QAM radio systems have become firmly established in the market place and the advent of 64 - QAM digital radios, with bit rates of up to 180 Mbits/s, has pushed the spectrum utilization efficiency to 4.5 bits/Hz.

The foremost objectives in 64 and 16-QAM digital microwave radio development have been (a) the designing of a high performance equipment, (b) new correction techniques for waveform distortion caused by fading, and (c) the solutions for various interference problems.

Newer 64-QAM digital radio systems operating in the 4,6, and 11 GHz bands have resulted in two, three, and four DS3 channel capacities respectively.

16-QAM digital radio system have become firmly established in the 6 GHz common carrier band. Using this modulation scheme, capacities as high as two DS3's (approximately 90 Mbps) have been achieved in a 30 MHz bandwidth.

The advantages of the proven 16-QAM systems include (a) transmitter emission efficiency of 3 bits/s/Hz, (b) superior convergence characteristics in the transmit spectrum and (c) greater immunity from adjacent channel interference than an 8 PSK system with similar capacity. Thus the system operates with less stringent cross polarization discrimination requirements. Some problem areas which had to be solved were the effects of transmitter nonlinearities and amplitude dispersions due to multipath fading.

A 6 GHz digital radio has been developed with system gain of better than 100 dB at BER = 10^{-6} using 16-QAM modulation and providing capacity as high as two DS-3's (approximately 90 Mbps). This radio is more immune to adjacent channel interference than existing 8-PSK systems operating in the same frequency band.

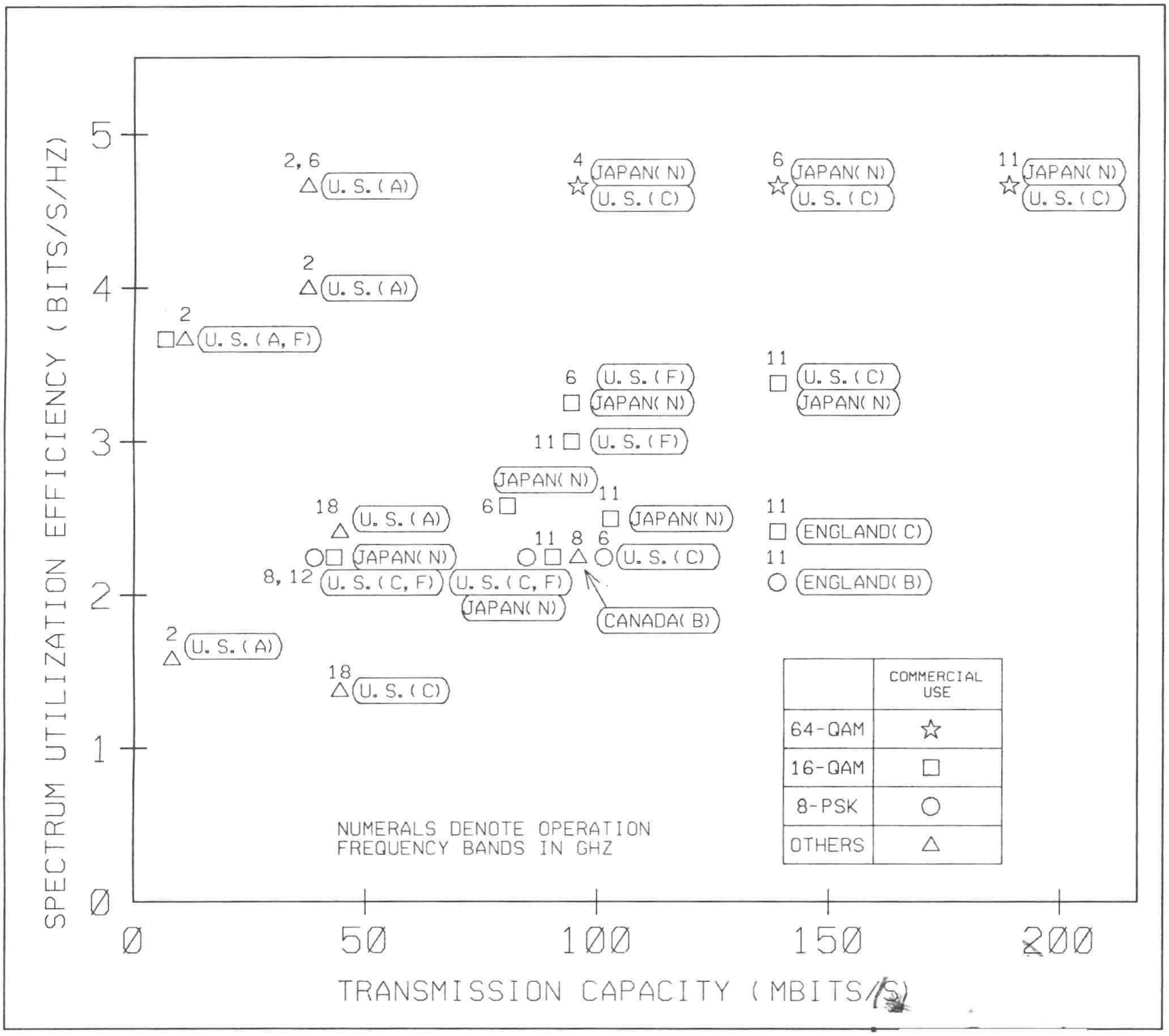

FIG. 1 STATE-OF-THE-ART DIGITAL MICROWAVE RADIO SYSTEMS THROUGHOUT THE WORLD.

One way to overcome the effects of nonlinearity on the BER performance is to utilize GaAs FET power amplifiers and predistortion circuits. The immunity to selective fading for the 16-QAM system is slightly less than that of the 8-PSK, 78Mbps system because of deficiencies in the adaptive equalizers used in the 16-QAM system. In order to satisfy the short-haul objectives, the improvement factor of the adaptive equalizer would have to be increased by 100% for a system without the advantage of space diversity.

From the spectrum utilization efficiency and compatibility viewpoints, a high capacity 16-QAM digital radio system is considered to be the most desirable. However, this system is very sensitive to waveform distortion caused by multipath fading. In order to minimize this distortion, new techniques such as space diversity and adaptive equalization are required.

The NTT communication laboratories (Japan) have developed new correction techniques for a 16-QAM digital radio system in the 4 and 5 GHz bands. The system is designated 4/5L-D1 with a transmission capacity of 200 Mbps per radio channel (2880 voice circuits) using dual polarization waves, space diversity, and adaptive equalization.

In general, spectrum utilization efficiency for a digital radio system is less than for a comparable analog system because the bit rate required for a 4 kHz voice signal is 64 Kbps. In order to transmit the same capacity as an FM system in the same band, a modulation method having a high spectrum utilization efficiency and dual polarization has to be developed.

The various digital transmission techniques employing coherent detection (demodulation) are listed below:

- o Binary Phase Shift Keying (BPSK)
- o Quaternary Phase Shift Keying (QPSK)
- o Offset Quaternary Phase Shift Keying (OQPSK)
- o 2-Level Quaternary Phase Shift Keying (2L-QAM)
- o Minimum Shift Keying (8-PSK)
- o Quadrature Partial Response Signaling (QPRS)
- o 4-Level Quadrature Amplitude Modulation (4L-QAM).

The above listing does not represent the complete choice of various techniques; however, all of the methods listed above do exhibit one or more of the following properties:

- o Ease of implementation
- o Good spectral efficiency
- o Low probability of error [P(e)]
- o High immunity to interfering signals

To improve the spectral and power efficiency of medium and high capacity digital microwave systems a new approach to the designs of 64-QAM Modems have been considered. The stringent specifications for out-of-band emission set by the FCC, DOC and other regulatory bodies along with consideration of the increasing density of terrestrial microwave and satellite traffic have made it necessary to look at modulation methods using better filtering and amplification techniques. To this end, intersymbol interference and jitter-free (IJF) filters and nonlinear amplifiers (NLA) are being incorporated into the modem design. The former is expected to contribute significantly to the improvement of the system spectral performance. This improvement compensates for spectral spreading resulting from nonlinear amplification.

Increasing use of digital radio under various conditions of operation have brought greater attention to the characterization of channel impairments, mainly the propagation anomalies caused by rain attenuation and multipath fading. Simple frequency-domain equalizers have been proposed and implemented for first-order correction of frequency response variations caused by multipath fading. Most recently digital radios using advanced modulation techniques have been described as achieving even higher spectral efficiencies. For example, 4-Level QAM has been used at 2 GHz to achieve 3 bps/Hz and appears promising at 6 GHz. The use of 7-Level QPRS at 8 GHz and the use of 7-Level Class IV partial response signaling with single-side-band modulation at 2 GHz have both been established. Each achieves 4 bps/Hz efficiency.

Digital radio stands today at about the same point as voiceband data was in the early 1970's when the widespread use of adaptive equalization was just beginning.

The problems unique to digital radio are being solved with new theories and techniques. In particular, the application of time-domain adaptive equalization to digital radio is an interesting possibility, and well within the reach of present day circuit technology. Not only can the effects of channel distortion during fading be greatly reduced, but the potential for cancellation of crosstalk from a parallel cross-polarized system exists as well. As digital radio systems mature, there is a distinct possibility they will be able to more efficiently utilize the available frequency spectrum than analog systems, thus furthering the development of all digital telephony.

System Considerations

A digital microwave radio system is an attractive transmission system to use in digitalizing a communication network. In designing a digital microwave radio system, special considerations need to be taken to facilitate the efficient use of the radio frequency spectrum; develop correction techniques for multipath fading distortion; and to effect compatibility with existing analog radio systems with respect to transmission capacity, frequency allocation, repeater spacing, repeater station facilities, etc.

The reliability of communications systems is of utmost importance as a factor in design consideration. Operators of communications system naturally expect reliability and Electric Power Utilities, because of the nature of their business, require highly reliable systems. In most cases, the reliability of the communications system directly affects the reliability of the power system because the communications system is designed as an integral part of the power system. The Electric Power Utilities usually specify their "reliability objective" in terms of the maximum allowable time of failure due to all causes, expressed as a percentage of total service time during a given period, over a given route length.

The availability objectives of most Electric Utilities for short-haul systems limit the two-way out-of-service time caused by propagation effects to 0.01% usually over a 400 km route for a nondiversity unprotected system during the worst month. For some specific systems such as main grid (500 kV) protection, an additional requirement of monthly outage less than 0.0001% per hop for a diversity system is specified (a diversity improvement of 100 times). Some of this outage allocation could be divided between equipment failure, atmospheric multipath, and rain caused fading. It is assumed that the antenna heights and site locations are set so that obstruction ("earth bulge") and terrain reflections are of insignificant consequence. Obstruction fading can be decreased by using higher towers, shorter hops or by increasing the hop fade margin. Where obstruction fading is known or expected to occur, increased clearances or shorter path lengths are assumed to be used; therefore, no allocations to obstruction fading is made and the entire annual allocation is applied to multipath fading.

As mentioned earlier, the most meaningful measure of performance in a digital system is the BER at the receiver digital multiplexer output. The BER depends primarily on the value of the received signal or carrier-to-noise ratio at the receiver. Consequently, system performance is determined by measuring Signal-to-Noise ratio at a particular BER. Generally, the voice quality at the receiving end of a system carrying traffic begins to deteriorate appreciably when the BER exceeds 10^{-3}. A BER of 10^{-6} is an acceptable minimum standard for 2400 bps data channels. The systems are, therefore, designed so that under normal conditions, the BER lies well below 10^{-9} most of the time and only reaches 10^{-6} threshold levels for a very small percentage of the time.

In a digital microwave radio system, Bit Error Rates exceeding the 10^{-6} threshold criteria are introduced if received carrier signals fade to threshold or by high level interference from a source having a frequency close to that of the desired carrier (co-channel interference).

CCIR Report 378-3, Appendix I, recommends the following performance objective for a hypothetical reference digital path:

1) The BER for the 2500 km reference circuit shall not exceed the following:

   a) 10^{-7} for more than 5% of any month averaged over any 10 minute interval.

   b) 10^{-3} for more than 0.05% of any month averaged over any 1 second interval.

Since these values are applicable only to a hypothetical reference path and no objectives are given for real circuits the following extrapolation is made: Assume that the hypothetical reference digital path is composed of six sections, each 400 km long; then for a radio link of up to 400 km the BER should not exceed:

1) 10^{-7} for 0.8% of any month averaged over any 10 minute interval.

2) 10^{-3} for 0.008% of any month averaged over any 1 second interval.

Thus, the most significant parameter for evaluating the quality of digital radio systems, is the outage time or the probability of exceeding a given bit error rate. The evaluation of outage time starts with the fade margin (difference between received RF power and threshold level for a given BER for the particular receiver design). Other factors which must be considered are multipath attenuation and rainfall attenuation; however, the effects of rain attenuation on propagation at frequencies below 10 GHz are negligible.

A useful measure that incorporates the parameters of interest into the design of a microwave system is the system gain. In its simplest form, applying only to the equipment, it is the difference between transmitter output power and the receiver threshold sensitivity for a given BER. Its value must be greater than, or at least equal to, the sum of the gains and losses which are external to the equipment. Mathematically, it is

$$G_s = P_t - C_{min} \geq FM + L_p + L_f + L_b - G_t - G_r$$

where G_s = system gain (dB)

P_t = transmitter output power (dBm), excluding antenna branching network

C_{min} = received carrier level (dBm) for a minimum quality objective. The C (dBm) is usually specified for a BER = 10^{-6}. This is also called the receiver threshold.

L_p = free space path loss attenuation between isotropic radiators

$$L_p = 92.4 + 20\log d + 20\log f$$

Where d = path length (km) and
f = carrier frequency (GHz)

L_f = feeder loss (loss factors for commonly used feeders are shown in Table II)

L_b = branching loss, that is, the total filter and circulator loss when transmitters and receivers are coupled to a single line. In an unprotected or space diversity system, the branching loss is typically about 2 dB. Branching losses for a frequency diversity system are shown in Table II.

G_t, G_r = gain of transmitter and receiver antennas, respectively, over an isotropic radiator. Although antenna gains are frequency dependent, for the sake of simplicity, mid-band gains as published in manufacturers' catalogs are shown in Table II.

FM = hop fade margin (dB) of a nondiversity system required to meet the reliability objective. This parameter is part of the Barnett-Vigant reliability formulas and may be solved explicity to determine the maximum allowable fade margin for a specified annual system availability.

TABLE II SYSTEM GAIN PARAMETERS

MID-BAND FREQUENCY (GHZ)	DIVERSITY SPACING (Δf/f%)*	FEEDER (L_f)		L_b	ANTENNA (G_t=G_r)	
		TYPE	LOSS/ 200 M (DB)	FREQ. DIVERSITY (DB)	SIZE (M)	GAIN (DB)
1.8	2.33	AIR-FILLED COAXIAL CABLE	10.8	5.0	2.4 3 3.7	31.2 33.2 34.7
7.4	4.24	EWP 64 ELLIPTICAL WAVEGUIDE	9.5	3.0	2.4 3 3.7	43.1 44.8 46.5
8.0	2	EWP 71 ELLIPTICAL WAVEGUIDE	13.0	3.0	2.4 3 3.7	43.8 45.6 47.3

Equation (1) below indicates the solution for an unprotected nondiversity system.

(1) $FM = 30 \log d + \log (6AB) - 10 \log (1 - R) - 70$

where 1-R = reliability objective (one way) for a 400 km route

A = roughness factor

4 for very smooth terrain, including over water

1 for average terrain with some roughness

1/4 for mountainous, very rough terrain

B = factor to convert worst-month probability to annual probability

1/2 for Great Lakes or similar hot, humid areas

1/4 for average inland areas

1/8 for mountainous or very dry areas

This fade margin is for availabilities on an annual basis. It may be used on a worst-month basis by setting B = 1.

To illustrate the relationship G_s-FM, the required system gain as a function of path length is shown in Fig. 2 for a nondiversity system planned for a power utility.

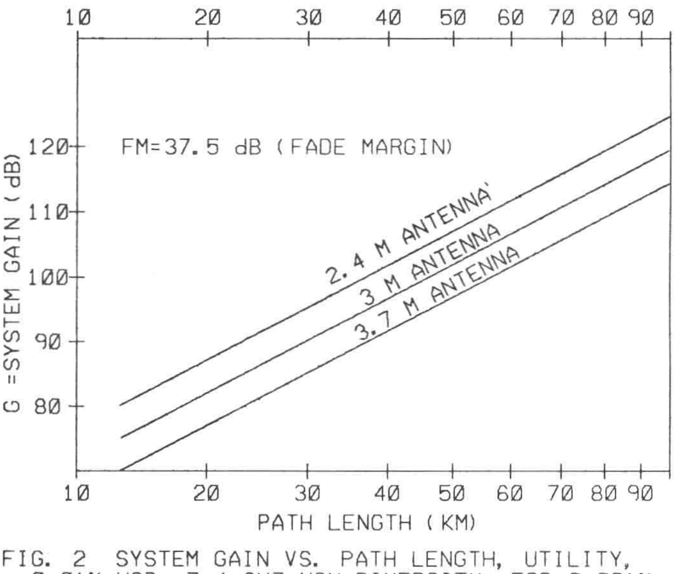

FIG. 2 SYSTEM GAIN VS. PATH LENGTH, UTILITY, 0.01% HOP, 7.4 GHZ NON-DIVERSITY. FOR 0.001%, ADD 10 DB TO G; FOR MOUNTAINOUS OR DRY, SUBTRACT 6 dB (A=1/4); FOR SMOOTH OR HUMID, ADD 6 dB (A=4).

With the use of the G_s equation different alternatives can be examined for quality engineering design; for example, by increasing system gain (a) longer hops can be obtained with the same reliability or (b) providing the possibility of saving sites or (c) for the same number of hops smaller antenna sizes can be used.

Multipath Attenuation

The gross behavior of the variation in transmission loss for many paths is explained by the refraction associated with the time varying vertical gradient of refractive index, and the formation of phase interference patterns due to diffraction and reflections by the earth's surface and atmospheric refractive index discontinuities. Reduction of the received signal below its free space value, as a result of their phenomenon is called multipath fading. Since the meteorological parameters also change with time, the observed result is the fluctuation of the received signal. In certain instances, ground reflected or other multipath rays will interfere with the direct ray, and the most severe fading occurs when the two effective components are of the same order of magnitude. If the radio path crosses water, and the geometry of the path is such that the point of reflection falls on the water, very severe fading can occur.

Deep fading causes a significant amount of both amplitude and delay distortion in the channel; in turn, this leads to intersymbol interference, a resulting decrease in system gain and, with it, the fade margin. This occurs at a time when the maximum system fade margin is desired. A degradation of the cross-polarization discrimination has also been observed during deep fading. This causes an increase in channel interference; the net result is, once again, a reduction in system gain.[1, 2, 3]

In Fig. 3, the dependence of phase distortion on frequency is shown. This empirical result is derived from observation over one path of nondiversity system.[4] The graph indicates, for example, that fades of 40 dB are accompanied by a linear time delay distortion which exceeds 2 ns/MHz for 50% of the fades.

The effects of the amplitude-slope distortion (linear distortion) on C/N degradation are illustrated in Fig. 4. In this figure computer-calculated C/N degradations of 22.5 M Baud (67.5 Mb/s)8-PSK and of 22.5 M Baud (45 Mb/s) QPSK and offset keyed QPSK systems are presented. In an offset QPSK (O-QPSK) system the binary symbols in the quadrature channel are one-half of a symbol interval shifted in reference to the symbols in the in-phase channel. Offset QPSK signals have a lower sideband regeneration when transmitted through nonlinear output amplifiers. From Fig. 4 it is evident that the higher-ary 8-PSK system having a higher bit rate (67.5 Mb/s) is much more sensitive to the amplitude-slope imperfection than the lower-speed (45 Mb/s) QPSK system. However, for amplitude slopes less than 0.45 dB/MHz, the performance of the 45 Mb/s 8-PSK system is better than the performance of the 45Mb/s QPSK system.

These field studies have sufficiently demonstrated that the long haul outage objectives can be met utilizing space diversity and linear amplitude equalization, for high capacity digital radio systems utilizing up to 16 signaling states of modulation.

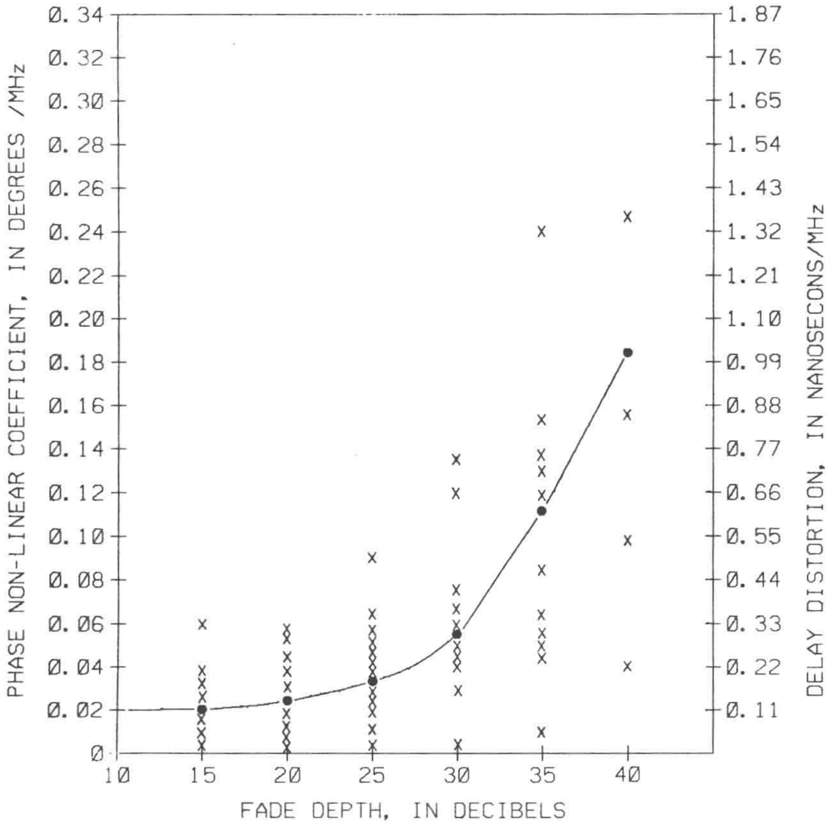

FIG. 3 DEPENDENCE OF PHASE NON-LINEARITY, CØ, ON FADE DEPTH.

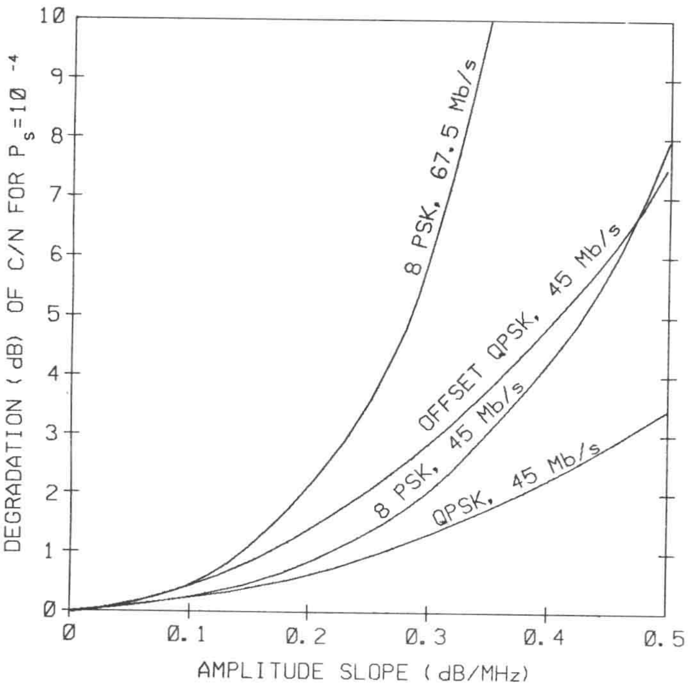

FIG. 4 COMPUTER-CALCULATED C/N DEGRADATIONS DUE TO AMPLITUDE SLOPE DISTORTION

Interference

The key to solving the problem of an interferred digital channel is to recognize that, from the overall system point of view, a decrease in system gain is equivalent to an increase in receiver threshold for a given carrier-to-interference ratio. Thus, a given P(e) can be maintained in the presence of interference by increasing the carrier-to-noise ratio, or the received carrier amplitude, of the victim receiver.

In an overall network design, the engineer will try to optimize the carrier-to-interference ratios so that the minimum fade margin, required to meet the CCIR objectives, is actually available on the interferred hop. The tolerance of digital channels to interference depends on the modulation system. In particular, modulation systems that require a low C/N for a certain BER threshold (e.g. 10^{-4}) are also more tolerant to interference.

In Fig. 5 the approximate increase in carrier-to-noise ratio required to maintain a specified error rate, plotted against carrier-to-interference ratio for 2-PSK, 4-PSK, 8-PSK, QPR (Class I Duobinary), 8-level, PAM-FM, and 16 PSK modulated carriers is shown. Note that the increments are all less than 10 dB. It should be possible to accommodate small values in the design as a decrease in system gain, in much the same way as is allowed for conventional feeder losses or decreases in transmitter power output.

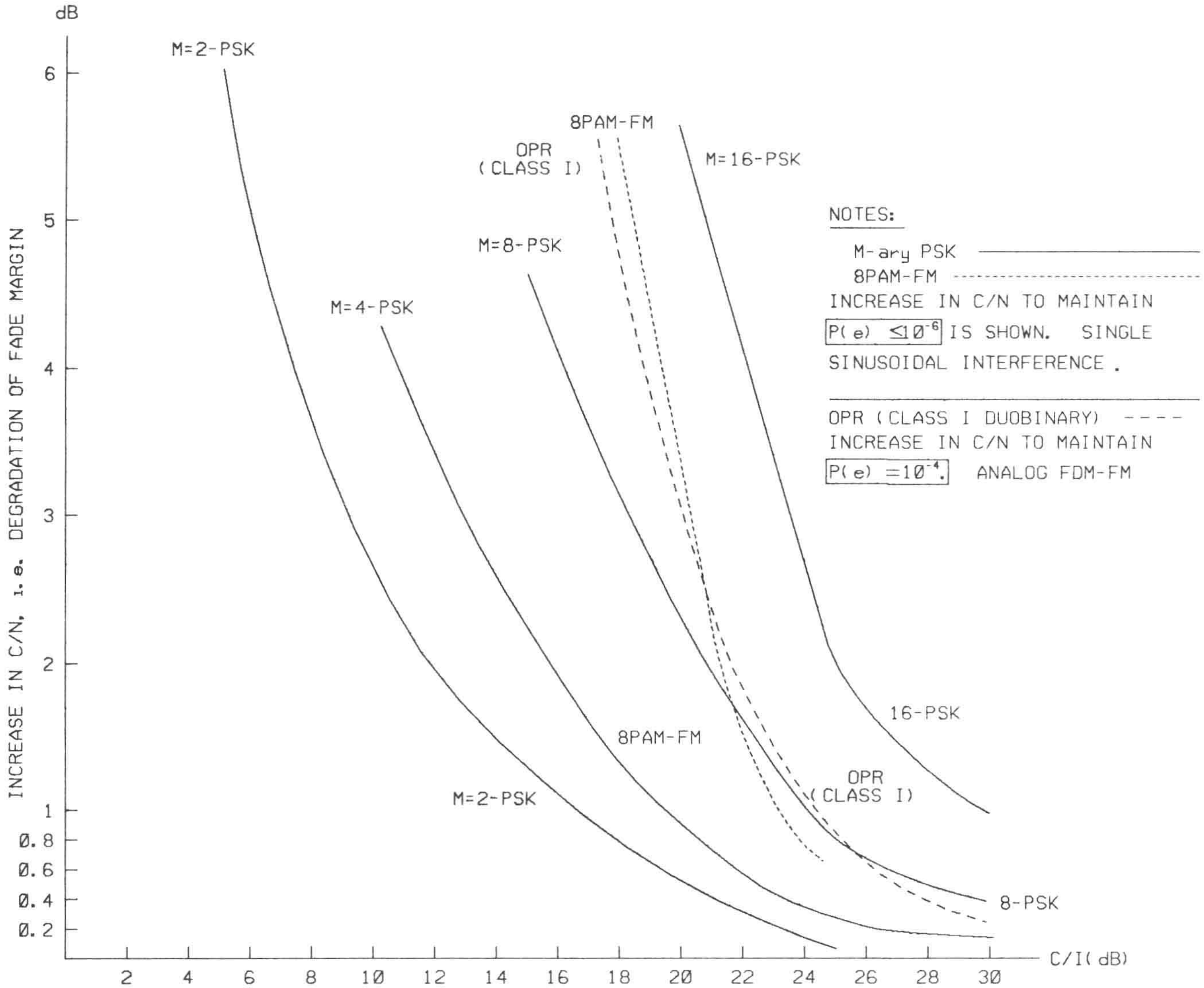

FIG. 5 INCREASE IN C/N TO MAINTAIN A SPECIFIED P(e) FOR CO-CHANNEL INTERFERENCE: M-ary PSK, OPR (CLASS I DUOBINARY) AND 8 PAM-FM.

The carrier to interference ratio can be evaluated by comparing the actual data of both the interferring and interferred links, thus obtaining the difference in power of the two signals of the common receiver input.

The actual C/I ratio on a certain receiver antenna input point can be evaluated from the following formula:

$$C/I = \alpha + \Delta L + \Delta P + \Delta G + \Delta F$$

Where:

α = antennas decoupling (positive)

ΔL = difference between the free space losses (positive when the interferred path is shorter than the interferring one)

ΔP = difference between the transmitted powers (positive when the transmitted power of the interferred path is higher than that of the interferring one)

ΔG = difference between the antenna gains (positive when the gain of the transmitting antenna is higher than that of the interferring one)

ΔF = difference between feeder lengths and branching losses (positive when the loss of the transmitting station is higher than that of the interferred one).

In a complex network, there are many interference configurations where the digital carrier must maintain the 15-20 dB of C/I also in faded conditions. Thus, the network design must, in principle, be such that the inteferring channel level is 15-20 dB below the threshold of the interferred channel. This fact sets requirements of antenna decoupling, filtering, etc., almost as stringent as those for analog networks.

It is well known that digital systems are highly tolerant to interference. An example of this is the common application of co-channel transmission of two digital carriers, where the correct operation of the system relies on cross polarization decoupling. This means that the digital signal is actually performing well even with a very low carrier-to-interference ratio (15-30 dB according to the modulation scheme). On this basis, it is frequently considered that the major problem in a mixed digital/analog network is represented by the digital to-analog interference.

The interference noise, due to a digital radio signal over an adjacent analog carrier, is due to the spillover of the radio spectrum into the analog band. This is shown, for an unfiltered PSK spectrum in Fig. 6. The residual spectrum density at fs-f (where fs is the spacing between two adjacent channels) is converted by FM demodulator into interference noise in the baseband channel at frequency f.

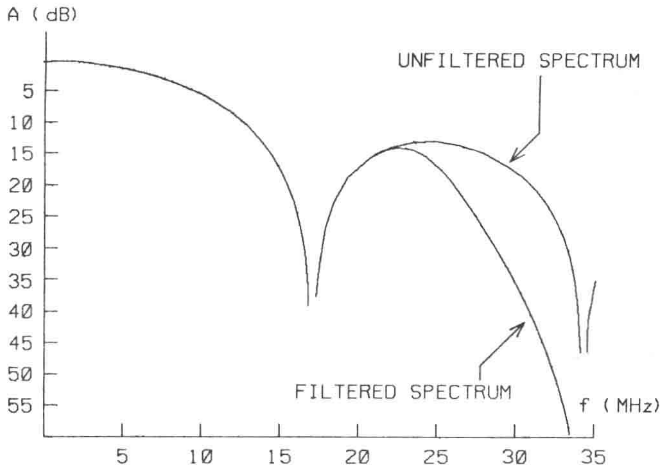

FIG. 6 RF SPECTRUM OF 34 Mb/s PCM SIGNAL 4 PSK MODULATION

The calculation can be carried out by means of the following formula:

$$S/Ni \left\{dBmOp\right\} = 3 + K + E(f) + 10 \log fm/BPS + 20 \log \Delta fo/f + Z(fs-f) + A - \varepsilon$$

Where:

f = analog carrier frequency for which the interference noise is calculated

fs = spacing between the digital and the analog carrier

K = 0 for one-sided interference and -3 for two-sided (symmetrical) interference

E(f) = analog carrier pre-emphasis value, for frequency f.

fm = modulating frequency

Bps = psophometric bandwidth

fo = nominal deviation of the interferred analog carrier

Z(fs-f)= attenuation at fs-f, with respect to fo, due to the spectrum separation and the RF filter characteristics

A = flat attenuation (e.g. cross-polarization decoupling, antenna protection, difference in output power, etc.)

ε = empirical factor that accounts for the effect of a modulated analog carrier.

Note that fm, modulating frequency, is the symbol rate which can be expressed as b/1 for a 2 PSK modulation, where b is the bit rate. For example, the value of fm for a 34 Mb/s transmission and 4 PSK modulation is 17 MHz. The worst channel from the point of view of interference noise is generally the top channel of the analog baseband. This is mainly due to the lower attenuating effect of the RF passband filter and a larger negative contribution by the factor of 20 log.

Generally, f is made equal to the baseband upper limit (e.g. 8.2 MHz for 1800 channels). It is to be noted that the whole formula, without the empirical factor, represents the interference noise, due to a modulated digital carrier, over an unmodulated analog system. Factor represents the noise increment with respect to the unmodulated case, due to the fact that the analog carrier is also modulated. This modulation produces further beatings of the components of the two signals, and increases the interference noise. An empirical value for this factor is nominally assumed to be 6 dB.

Protection Systems

The main contributions to the unavailability of a network are categorized as follows:

1) Those controllable by equipment and route design (fading).

2) Those caused by operational activities (maintenance, system expansion, etc.)

3) catastrophies (fires, antenna/feeder system failures).

About 20% of operational unavailability is apportioned to (1), above.

To meet the stringent availability objectives most digital microwave systems include protection channels and automatic switching systems. These systems have been successfully used to provide excellent P(e) performance and also to minimize loss of service resulting from fading or equipment failure. The systems of interest to us here are the frequency diversity, space diversity and hot-standby systems.

The effect of fading on operational unavailability can be minimized by frequency or space diversity techniques, as illustrated in Fig. 7. Both of these techniques are based on the hypothesis that simultaneous fading on both radio transmission paths is unlikely.

In a frequency diversity configuration the same digital information is fed into two transmitter, Tx1 and Tx2. A wide radio frequency separation of these transmitters ensures less correlation between the fades of the individual radiowaves; thus, better system performance is realized.

Frequency diversity systems are used most frequently for the protection and performance improvement of FDM/FM microwave systems.[5, 6, 7] The authorized users and the number of radio channels available for this type of protection has been limited in the United States by FCC regulations introduced in the early 1970's.[8]

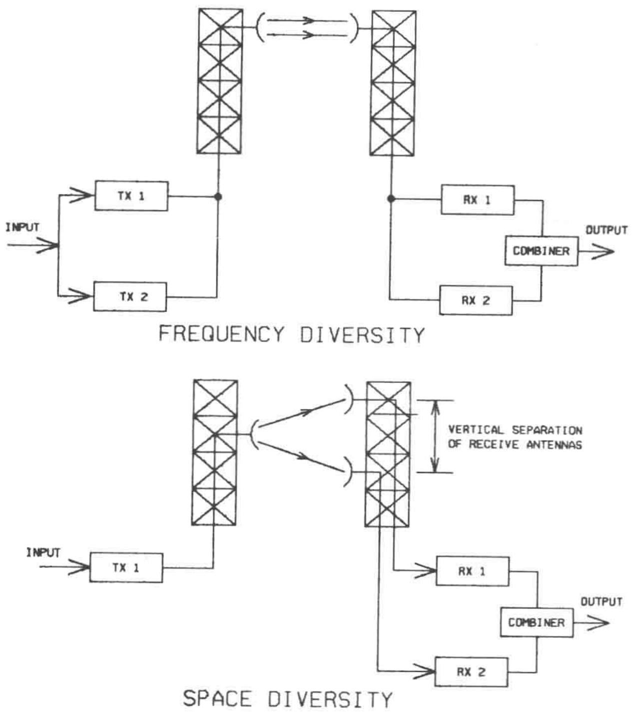

FIG. 7 FREQUENCY DIVERSITY AND SPACE DIVERSITY ACCOMPLISH SIMILAR ENDS BUT USE DIFFERENT EQUIPMENT CONFIGURATIONS.

This diversity technique provides the following improvement:

$$I_f = C \times \frac{\Delta f}{f} \times 10^{\frac{m}{10}}$$

Where:

I_f = improvement factor for frequency diversity

C	=	1	for	2 GHz band
		0.5	for	4 GHz band
		0.25	for	6 & 7 GHz band
		0.125	for	8 GHz band
		0.083	for	11 GHz band
		0.070	for	13 GHz band
		0.065	for	15 GHz band

Δf = Minimum frequency spacing between standby and main carriers (GHz)

m = Fade margin (dB)

Frequency diversity techniques are also used for M-for-N protection switching arrangements, in which M protection channels are used to protect N information carrying (working) channels.

In Fig. 8 the block diagram of a typical 2-for-5 frequency diversity protection switching system is illustrated. Under normal propagation conditions, the five working channels are connected through the switching elements. The two protection channels may carry extra customer traffic or may carry only a digital test pattern. The monitors at the receiver end, located prior to the receiver switch, monitor the performance of the working channels and the protection channels. For this purpose, on-line pseudo error monitors could be used as they are reliable as well as fast in-service monitors. Once the P(e) of one of the working channels is degraded to the threshold performance [e.g., to P(e) = 10^{-6}], the pseudo-monitor provides an alarm to the receiver logic. This logic sends a signal to the transmitter logic which, in turn, switches the traffic to one of the protection channels. This channel operates at a different RF frequency. Traffic is switched back to the working channel, once it recovers. The protection switching operation must be fast, so as to react to multipath fading and minimize interruption of service when maintenance operations are performed on the system.

In the space diversity system the same radio frequency band is used for the transmission of the digital information. Diversity results normally from separating the two receiver antennas vertically. This ensures that the received radio waves travel through different transmission paths; thus, they are not likely to be affected simultaneously by fading.