# DIGITAL RADIO: SYSTEMS, MARKETS AND TRENDS

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## Abstract

Microwave digital radios are now entering operational service. 8 PSK RF modulated radios are very attractive for high channel density applications. This paper reviews some of the basic design considerations for digital radios, discusses current state-of-the-art and also markets, present and future.

## Introduction

For more than two decades, FM/FDM analog microwave radios have been used for line-of-sight transmission in telecommunication systems. In the past few years, as a result of the increasing application of PCM voice channels, the introduction of the large digital switch, and the growth of data communications, the need for microwave digital transmission has become apparent. The current outlook for digital radio in commercial and government applications is very promising.

The primary differences between a digital radio and an analog radio are the modulation and baseband systems. System parameters and performance are very different for the two radio types.

The advantages of a digital radio system over an analog system are:

1) Multiplexing Cost - The cost of a digital multiplex system is less than one-half the cost of an analog FDM system.

2) Noise Performance - The noise in a digital system with regeneration at each repeater is independent of the number of hops, whereas the noise in an analog system builds up as A log N, (N is number of hops and $10<A<15$ dB).

3) Signal-to-Noise Level - Acceptable S/N at threshold levels are 15-20 dB lower in the digital radio than in the analog radio.

4) Interference - The digital radio is much less susceptible to degradation of performance by interference than the analog radio.

The digital radio, however, is less efficient in spectrum utilization than the analog radio. The voice channel capacity of current high density PCM digital radios operating in the 6 and 11 GHz common carrier bands is 25% less than the US analog capacity and 50% less than CCIR analog capacity. Proposed high density single sideband analog radios will have four times the channel capacity of present digital radios. Since the radio spectrum is a limited resource, digital radio in spite of many inherent advantages will ultimately have to be competitive with other approaches in spectrum utilization.

The first large digital installation in the US was the 42 MB/S Datran system in the early 1970's. Full development of commercial microwave digital radio in the US was delayed until late 1974 when the FCC issued the regulations governing digital transmission in the common carrier bands. The dockets, among other issues, specified a spectrum mask shown in Figure 1 that the radiation had to be contained within, a continuous spectrum with no line spectra, and a minimum channel loading of 1152 channels in a 40 MHz bandwidth at 11 GHz, a 30 MHz bandwidth at 6 GHz, and a 20 MHz bandwidth at 4 GHz. Since the issuance of the dockets several US companies and a Japanese company have placed common carrier band equipment on the market and a considerable number of systems have been or will shortly be placed into operation.

In this paper, the fundamental design considerations of microwave digital radio, hardware and performance will be discussed. Finally, current and future applications will be considered.

## PCM Hierarchy

Digital radios for common carrier applications must be compatible with standardized PCM interfaces. The US and the international PCM hierarchies (CCITT) are different as shown in Table I, however, both are based on coding a voice channel with 64 KB/S. The group level in the US hierarchy is 24 voice channels with signaling included while the CCITT group is 30 voice channels plus two channels for signaling.

## Design Parameters for Microwave Digital Radio

The key design and performance parameters of microwave digital radios are system gain, threshold level for a specific error rate, spectrum efficiency measured in Bits/Hz of radiated spectrum, and interference susceptibility. These parameters are a function of modulation technique, filtering, transmitter power and system noise figure.

System gain, M, is defined as the ratio of transmitter power after filtering to receive signal (for a specific error rate) prior to preselector filtering.

$$M = \frac{P_T \cdot L}{(S/N)\cdot F_n kTB} = \frac{(4\pi R)^2}{\lambda^2 G_T L_T \cdot G_R L_R L_F}, \qquad (1)$$

where $P_T$ is power amplifier power output, L is transmit filter loss, R is path length, $G_T$ and $G_R$ and transmitter and receive antenna gains and $L_T$ and $L_R$ are transmit and receive waveguide losses and $L_F$ is the loss during faded condition. S/N is the signal to noise ratio at preselector input for a specific error rate. Eq. 1 shows the trade-off for a specific path between power, noise figure, and threshold S/N. The higher the system gain, the less antenna gain required and consequently the lower the cost of the installation.

Channel capacity in Bits/Hz has a fundamental limit derived by Shannon in his early work on information theory. Figure 2 illustrates the fundamental limit and also shows the theoretical spectrum capabilities achievable by various modulation techniques, as well as the state-of-the art for 6 and 11 GHz 8 PSK radios. Actual radios require several dB higher S/N than the theoretical spectrum capabilities due to filtering, encoding, temperature variations and other practical considerations. The minimum spectrum efficiencies to meet the FCC requirement of 1152 voice channels are approximately 2 and 2.68 Bits/Hz at 11 and 6 GHz respectively. The minimum capacity, 1152 voice channels, is not a natural interface in the US PCM hierarchy and is not convenient in a system application. A higher capacity, 1344 voice channels, is much more practical since this capacity can be achieved with 2-DS3 signals. (See Table I.) The required spectrum efficiencies for a 2-DS3 radio are 2.25 and 3 Bits/Hz at 11 and 6 GHz respectively.

Since FCC permits the use of two orthogonally polarized radio channels on the same frequency, two channels of 4 PSK, or one channel of 8 PSK (or higher level PSK system) and higher level ASK-PSK system may be used to achieve spectrum densities up to 3 Bits/Hz. The cross polarized 4 PSK system appears to meet the required spectrum efficiency at the lowest S/N, however, as discussed in a later section, other difficulties tend to preclude its use, even though some early systems utilized this approach.

Intersymbol interference, or the spill over from preceding symbols at the sampling time of a specific symbol, degrades error performance. Intersymbol interference can be minimized by properly shaping pulses so that all pulses except the one being sampled have a zero value at the time of sampling. As the signal is passed through any band limited element such as a baseband amplifier, upconverter, power amplifier, IF amplifier, and system filters, intersymbol interference may be produced. The total system transfer function must be taken into account when designing the highest performance radio. Figure 3 shows the degradation of error rate considering only effects of RF filtering. The filters used in the calculation of Figure 3 are all based on achieving a radiated spectrum that fits in the mask shown in Figure 1.

External interference arising from various sources including adjacent or co-channel emissions also leads to degradation of error performance. The degradation produced by a CW tone on an 8 PSK signal is shown in Figure 4.

## Modulation Systems

Some of the modulation systems capable of placing digital information on an RF carrier are listed in Figure 2. The modulating data stream may be applied to an IF frequency and upconverted to RF or it may be directly applied to the RF carrier. Signals applied at IF frequency and upconverted are subjected to several band limiting stages prior to power amplification, and as mentioned earlier this can for high data rates, introduce degradation of error rate. Direct RF modulation produces the minimum degradation.

ASK systems or combined ASK-PSK systems require linear amplifiers to reproduce the amplitude levels. A phase modulated signal does present 100% AM for a 180° transition, however, if the phase transition time is kept low, i.e. a small fraction of the baud rate, and if the spectrum filtering is done after amplification in a typical nonlinear solid state amplifier, the degradation due to AM to PM will be small. A disadvantage of full spectrum shaping after amplification is higher power loss.

Interference effects are minimum for 4 PSK, several dB worse at 8 PSK and considerably worse in other systems. Since digital radios for common carrier service operate multi radio channel environments, with 40 MHz adjacent channel spacing at 11 GHz and 30 MHz spacing at 6 GHz, interference effects must be minimized.

## Cross Polarization vs Single Polarization

As mentioned above, the FCC permits the utilization of two transmitters in the same channel but on orthogonal polarizations to double the spectrum capacity. PSK digital systems have fairly good resistance to interference and carrier to interference levels of 25 dB will degrade performance by 1 dB or less. Since under normal propagation conditions, good antennas have cross-polarization discrimination of 25-35 dB, two orthogonally polarized signals in the same channel may co-exist with little degradation. Unfortunately under fading the cross-polarization discrimination can decrease substantially. Figure 5 shows data[1] on measured values of cross-polarization discrimination (XPD). Note that during certain periods the XPD drops more than 30 dB. During those periods, interference effects for cross-pol operation can result in very significant degradation.

In addition to XPD deterioration under faded conditions, cross-polarized systems require twice as much radio equipment as single-pol systems, also protection for fully expanded radio systems is very difficult with a cross-polarized system.

## Digital Radio Systems

Based on the above, it appears that an optimum choice of a high density digital radio system for the common carrier bands is an 8 PSK, RF modulated radio. While 8 PSK does have poorer noise and interference performance than 4 PSK, it does have superior spectral efficiency and does not require cross-polarized operation. An 8 PSK, RF modulated 11 GHz, 90 MB/S 2.25 Bit/Hz digital radio is shown in Figure 6. This radio utilized phase locked Gunn sources for transmitter and receiver, a stabilized IMPATT power amplifier, a 5 cell coupled cylindrical cavity Tchebychev transmit filter, and a three section waveguide, circulator coupled path length phase modulator. The transmit filter is a sealed invar structure to insure long term stability. All equalization is accomplished in the IF amplifier. The radio has 1W power out for frequency diversity operation, has a maximum receive carrier level of -68 dBm for $10^{-6}$ bit error rate and has 98 dB minimum system gain. A 6 GHz version of the radio has a spectrum efficiency of 3 Bits/Hz, 5W power out (using TWT) and also has 98 dB minimum system gain.

The RF modulation technique is not suitable for low voice channel densities as might be required in Government applications since the transmit filter problem became unmanageable. For these applications 8 PSK is still useful and can be applied at IF. In the lower bit rate case, the band limiting caused by the various circuit elements does not play a significant role.

Digital radios operating in the higher frequency bands, 20 and 39 GHz, are currently not subject to the same FCC restrictions as the lower frequency common carrier band radios. Radios in these bands have been built and 20 GHz test systems are operational in Japan with a 400 MB/S 4 PSK radio and in the US with a 274 MB/S 4 PSK radio. Both radios use RF modulation.

A low density (192 channel) 2 GHz band for digital radio has been defined by the FCC for spur routes. Both single-pol and cross-pol radios for this band have been developed.

For several low density applications analog and digital signals are combined on the baseband and transmitted as a hybrid signal on FM analog radio. The primary use for this service, usually called DUV, or Data Under Voice, is for the industrial market. The data signal generally does not exceed the "T" line (1.544 MB/S). Much of the traffic in industrial band radios is low speed digital signals that are coupled to analog basebands through modems. The FCC has not yet drawn up the regulations for digital radios operating in the industrial bands.

## Markets

The initial market for high density microwave digital radio is the common carrier market. One of the primary forces driving this market is the large PCM network and the introduction of digital switches. The initial entry of the special common carriers into digital transmission was ill fated, however, future markets may open. At least six domestic suppliers and one off shore supplier are offering and selling radios for the US telephone market. Many of the ATT companies are installing or developing plans for a large growth of digital systems. At this time the independent telephone companies are just starting to enter the digital radio transmission picture. Several companies are offering low density 2 GHz digital radios.

The industrial market appears to have good promise for digital transmission since much of the traffic hauled on private systems is data. Since no FCC regulations exist, manufacturers have not yet released digital radios for sale to industrial users. It will probably be several years before purely products are sold to industrial users. During the interim hybrid systems and data modems will be used with analog radios.

The Government is moving towards all digital communications. Government owned digital networks will be developed over the next several years using radios in the 4.4-5, 7.2-8.4 and 15 GHz bands. The initial installation of these radios will probably be in Europe for the US Digital European Backbone (DEB) system. The first phase of DEB is being installed with FM, 1 Bit/Hz 3-level partial response radios. The Government will also lease many digital channels from common carriers in the US, thus increasing sales of equipment.

The international market was not discussed in this paper. Japan is well ahead of the US in manufacturing and installation of digital radios - the Japanese market is essentially closed to US manufacturers. The European market is developing slowly, does not have developed standards and also, except in a few cases, is closed to US manufacturers. Currently with a few exceptions, the developing countries are installing analog systems.

## Reference

1. W. T. Barnett, "Determination of Cross-Polarization Discrimination During Rain and Multipath at 4 GHz", Proceeding 1974 ICC, Minneapolis, Minn., pp 12D-1.

TABLE I

PCM HIERARCHY

| | LEVEL | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| US<br>VOICE CHANNEL<br>BIT RATE<br>DESIGNATION | 24<br>1.544 MBS<br>DS1 | 96<br>6.312 MBS<br>DS2 | 672<br>44.736 MBS<br>DS3 | 4032<br>274 MBS<br>DS4 |
| EUROPE<br>VOICE CHANNEL<br>BIT RATE | 30<br>2.048 MBS | 120<br>8.448 MBS | 480<br>34.368 MBS | 1920<br>140 MBS |

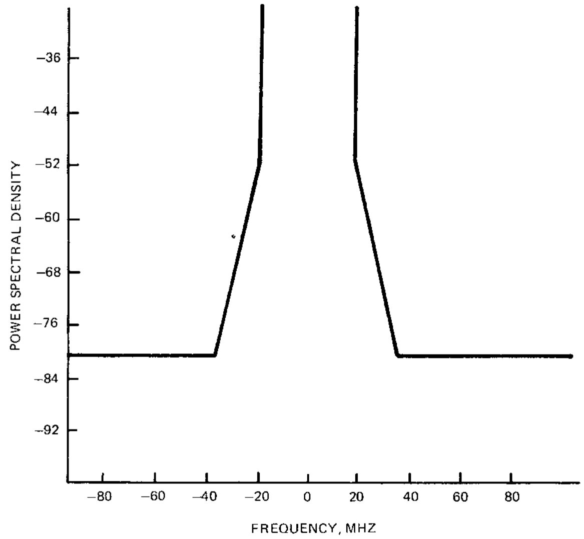


**FIG. 1 FCC SPECTRUM MASK FOR 11 GHZ DIGITAL RADIO**

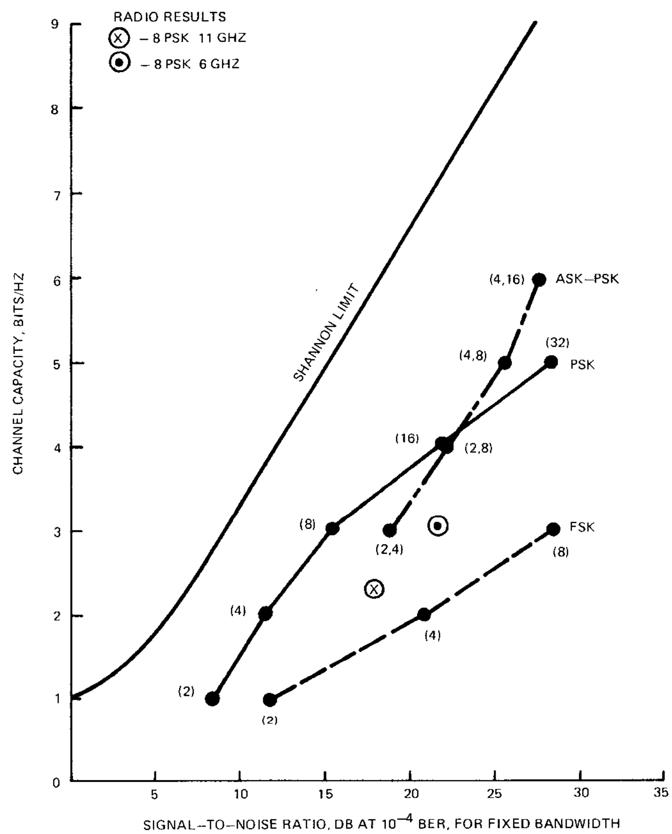


**FIG. 2 CHANNEL CAPACITY FOR VARIOUS MODULATION METHODS. NUMBERS IN PARENTHESIS ARE MODULATION LEVELS.**

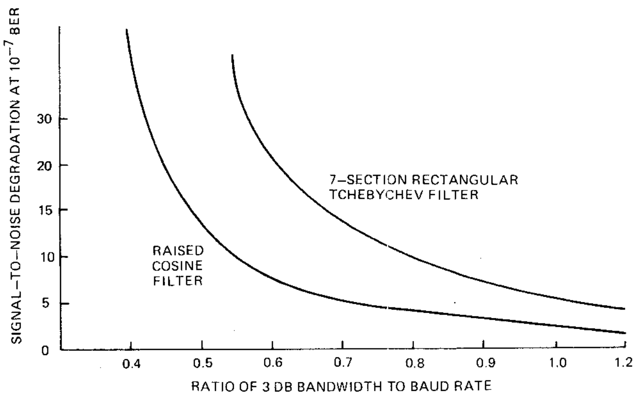


**FIG. 3 THRESHOLD DEGRADATION AS FUNCTION OF FILTERING**

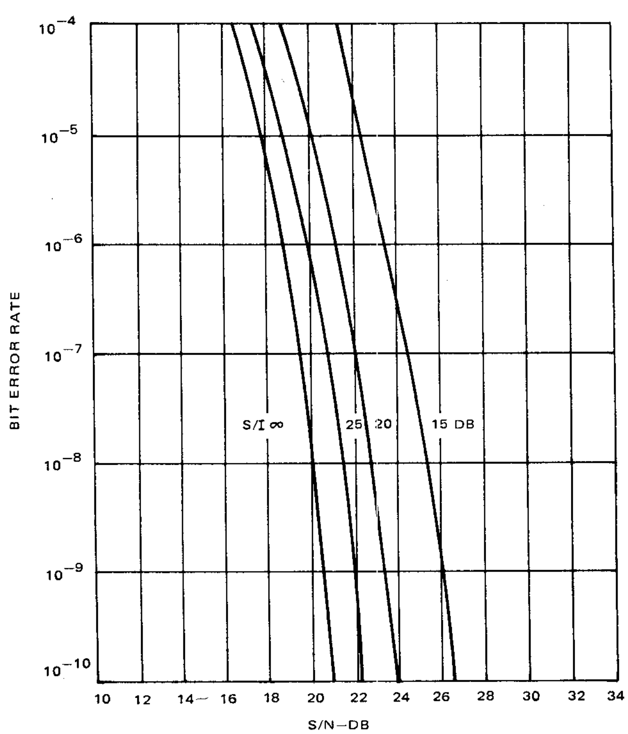


**FIG. 4 BER AS FUNCTION OF SIGNAL–TO–NOISE RATIO FOR UNFILTERED 8 PSK. S/I IS RATIO OF SIGNAL–TO–INTERFERENCE.**

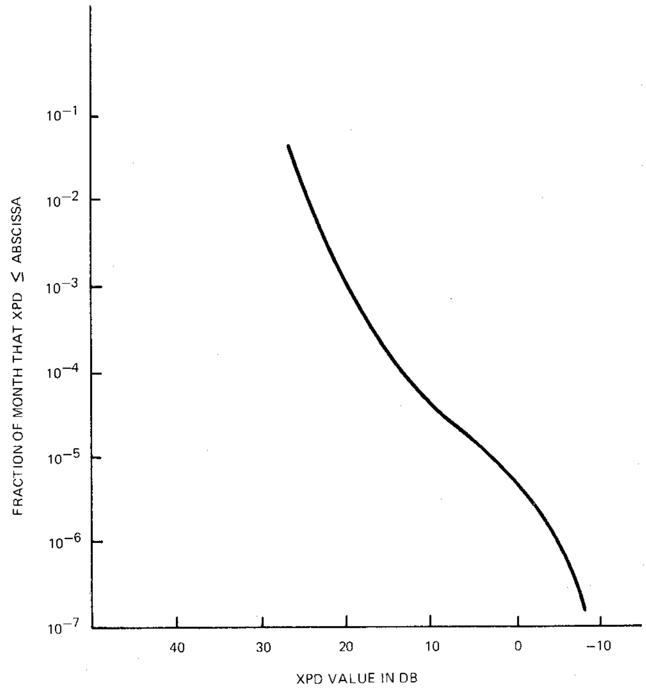


**FIG. 5 CROSS POLARIZATION DISCRIMINATION FOR FADES 40 DB AT 4.2 GHZ REFERENCE W.T. BARNETT (1)**

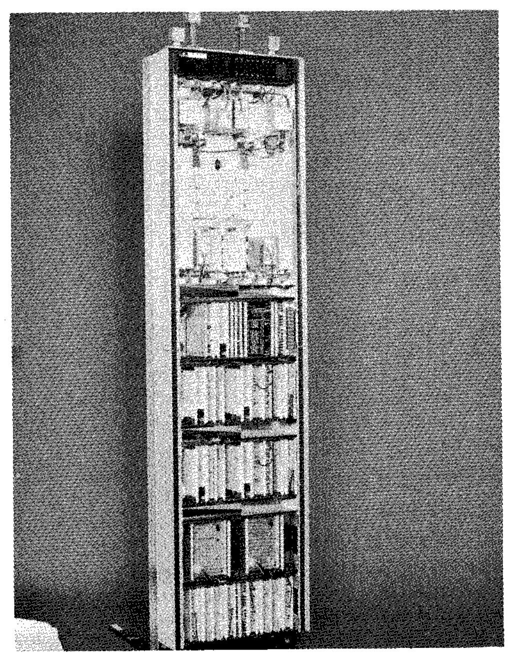

**FIG. 6 11 GHZ, 90 MB/S, 2–DS–3 RADIO**