Telecommunications by Microwave Digital Radio

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In this introductory article in our tutorial series on microwave digital radio, various problem areas are surveyed and some solutions are offered

Since the early 1970s, microwave radio has been gaining in importance as a transmission medium for digital communications [1]. This growth has been driven to a great extent by the large-scale introduction of digital switching. The first digital microwave radio systems were somewhat rudimentary, utilizing quaternary phase-shift keying (QPSK) modulation and achieving a spectral efficiency of less than 2 bits/sec/Hz. However, since the mid-1970s major technical advances have been made, and today spectral efficiencies of more than 4 bits/sec/Hz are commonplace [2], with even higher efficiencies in the offing [3].

Digital radios are susceptible to propagation anomalies, such as dispersive fading and ducting, and are extremely sensitive to equipment imperfections. In order to develop high-capacity systems with the necessary performance levels, such problems have had to be overcome [4]. Through cooperative research efforts on a worldwide basis and the relatively free reporting of results in a timely manner, enormous gains in both efficiency and performance have been made.

This article is the introduction in a tutorial series of six articles dealing with various aspects of microwave digital radio that will appear in this and succeeding issues of *Communications Magazine*. The other five articles will describe in some detail the problems of digital radio, the approaches that have been taken toward their solution, and the directions in which—in the judgment of the various authors—high-capacity digital radio systems are moving. In this introductory treatment, we will merely survey the various problem areas, touch lightly on some of the approaches that are being taken toward their solution, and then refer the reader to the more detailed articles later in the series.

Network and Regulatory Issues

The telecommunications administrations of most countries are now engaged in digitalizing their transmission and switching facilities, as a key step toward establishing an integrated digital network. The present transmission network consists of a mix of cable (fiber-optic and coaxial), satellite, and line-of-sight (analog and digital) radio systems. The introduction of digital radio systems can be successful only if they meet existing transmission performance standards, their spectral efficiencies are compatible with those of their analog counterparts, and their coexistence with other transmission systems does not lead to performance degradations.

To ensure that these criteria are adapted uniformly on a worldwide basis, regulatory bodies such as CCIR, CCITT, and FCC have approved a number of reports and recommendations [5,6]. Three main issues discussed in such reports are (1) data rates, (2) frequency channelization, and (3) out-of-band emissions and interference. In this section, we will briefly examine these topics.

Data Rates

The standard bit rate for a digital voice circuit is 64 kb/s. In the United States, the digital hierarchy begins with the time-division multiplexing of 24 such circuits

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(plus framing bits) to form a 1.544-Mb/s signal called DS-1. The second-level signal, DS-2, is four multiplexed DS-1 signals, or 96 voice circuits at about 6.3 Mb/s; the DS-3 signal is 672 voice circuits at about 45 Mb/s; and so on. In most European nations, the first digital signal level is 30 multiplexed voice circuits at about 2 Mb/s. As a result, the third- and fourth-level signals contain 120 and 480 voice circuits, at about 34 Mb/s and 140 Mb/s, respectively. The data rates 34 Mb/s, 140 Mb/s, and 45 Mb/s (or multiples thereof) figure prominently in digital radio transmission, as we shall see.

Frequency Channelization

Channel plans for carrier radio systems now exist for bands from 2 GHz to 40 GHz, those below 12 GHz being most commonly used for long-haul digital radio. Most countries have elected to use the same channelizations for analog and digital systems in order to facilitate coexistence on the same routes.

As a typical example, the 4-, 6-, and 11-GHz common-carrier bands in the United States are each 500 MHz wide, with channel spacings of 20, 29.65, and 40 MHz, respectively. In all cases, polarizations are assigned to channels in such a way that adjacent channels always operate on orthogonal polarizations.

The move to digital radio in the United States was aided by several important actions of the Federal Communications Commission (FCC) in the 1970s. In particular, Docket 19311 established the framework for manufacturers of digital microwave equipment [6]. Some of its major provisions included a requirement that radios operating in the 4-, 6-, and 11-GHz bands have minimum capacities of 1152 voice circuits per channel. To be consistent with the digital hierarchy, then, the nearest multiple of 672 voice circuits above 1152 (at a minimum) must be transmitted in each radio channel. This corresponds to 1344 voice circuits, or two DS-3 signals at 90 Mb/s.

To accommodate 90 Mb/s in the 20-MHz channels of a 4-GHz system requires a spectral efficiency of 4.5 bits/sec/Hz. The corresponding requirements for 6- and 11-GHz systems are 3.0 and 2.25 bits/sec/Hz, respectively. Earlier digital radio systems were designed for the latter two bands, and met the spectral efficiency requirements by using such modulations as 8-level phase shift keying (8-PSK), 9-level quadrature partial response signaling (9-QPRS), and 16-level quadrature amplitude modulation (16-QAM). More recent systems are using 64-QAM to achieve 4.5 bits/sec/Hz, and prototype systems using 256-QAM have been reported.

Out-of-band Emissions and Interference

Digital modulations are particularly notorious for producing high out-of-band emissions. To limit the resulting potential for adjacent channel interference, FCC Docket 19311 has defined a spectral emission "mask" which places limits on the transmitted spectral density-to-total power ratio as a function of frequency. Comparable rules are used by other administrations to control out-of-band emissions.

Other kinds of interference are important as well, for example, co-channel interference from other systems and cross-polarization interference in systems with dually-polarized signals. An early argument in favor of digital radio was signal robustness, that is, high tolerance to interference. With the advent of high-level modulations, however, the consideration of interference has become increasingly important. System designers must take note of even relatively weak sources of interference, for example, satellite downlinks in shared bands, waveguide echos, etc. Also, antenna cross-polarization discriminations must be very good in order to control adjacent channel interference and permit the effective operation of dual-pol systems.

Major Technical Issues

Digital radio must provide a transmission path which has essentially the same reliability and availability as its major competitors, namely, optical fiber and satellite systems. The major advantage of digital radio over optical fiber is its lower installation cost, and its primary advantage over satellite transmission is its much smaller propagation delay. The major technical issues facing the designer of high-capacity digital radio systems may be broadly classed as propagation problems and equipment requirements. In this section, we briefly examine both.

Propagation Problems

Most of the time, a line-of-sight microwave radio channel is a nondispersive transmission medium capable of highly reliable, high-speed digital transmission. However, because it is a natural medium, anomalous propagation conditions exist for some fraction of the time, and these can cause very severe degradation in radio systems performance.

These conditions manifest themselves through what is referred to as multipath fading [8]. Fading almost always consists of a combination of flat and frequency-selective components. The flat component is a time-varying, frequency-independent attenuation of the channel response and, hence, of the signal. This attenuation can be thought of as the median, over a broad frequency range, of the radio path's power gain. It is referred to as the *median depression,* and is usually compensated for over a wide dynamic range by the automatic gain control of the receiver. The remaining (frequency-selective) component of the fade is the frequency variation of the power response about the median depression. It manifests itself either as a monotonic gain change (or *slope*) across the radio channel bandwidth, or as a dip (or *notch*) within that bandwidth. Figure 1 illustrates a faded channel frequency response in which the various parameters that characterize fading are identified.

Multipath fading arises from the fact that the signal propagates along several paths, each of different electrical length. At the receiver, these relatively delayed signal components interfere with each other, and this leads to the frequency-selective effects described above.

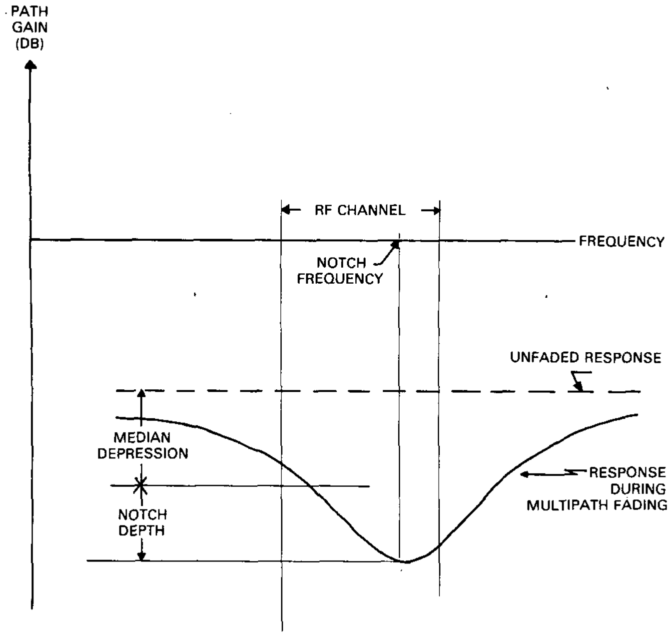

Fig. 1. Radio channel responses.

In order to design radio equipment to work in this environment, it is essential that the system designer have realistic and readily usable models of the multipath channel response. The development of statistical modes for use in system design is the subject of the third paper of this series [9].

The frequency-selective notches referred to above can vary in depth from 0 dB to more than 40 dB and, if left uncompensated, can cause severe degradation in the performance of a radio receiver. In fact, an uncompensated selective notch of as little as 5 dB in depth could effectively cause a radio link to be out of service, a condition that is usually referred to as an *outage*. (The 5-dB number is only representative; in reality, the notch depth that produces an outage would depend on such factors as notch frequency (measured with respect to the channel center frequency, Fig. 1), type of modulation, and reception technique.)

A number of convenient means of characterizing the sensitivity of radio equipment to propagation anomalies have been developed, the most widely used of which is the so-called signature curve [10] exemplified in Fig. 2. Each enclosed area represents, for a given modulation and type of reception, the notch depth/notch frequency region over which some specified bit error rate (usually 10^{-3}) is exceeded. The boundary curve for each such region is called the *equipment signature*. The shape of the signature for the unequalized receiver shown in Fig. 2 is fairly typical, and so, for obvious reasons, signature curves of notch depth vs. notch frequency are often called "M curves." Some digital radio engineers display the vertical scale with the reverse polarity, that is, with notch depth expressed as a *positive* quantity, in which case the signatures are inverted, and are hence called "W curves." Both M curves and W curves will be in evidence throughout this tutorial series.

During the past several years, one of the major achievements in radio design has been the development of sophisticated equalization techniques to combat the deleterious effect of multipath fading. Historically, the first equalizer strategy consisted of the combination of an amplitude slope equalizer, which compensates for inband gain slope, and a space diversity receiver, which compensates for notches or dips in the received frequency response (cf [11]). These techniques were sufficient for the relatively simple modulation techniques used in the early systems. With the continuing increase in bit rates and the concomitant increase in modulation complexity, however, such an approach soon proved to be inadequate, and more sophisticated equalizers were developed. These have mainly consisted of adaptive transversal equalizers (cf [12]) or decision feedback equalizers (cf [13]) used either alone or in combination with slope equalizers and (in most instances today) space diversity receivers. Many of these adaptive measures are based on the voiceband equalization techniques developed in the 1960s.

A block diagram of a receiver that includes space diversity combining, an IF slope equalizer, and a baseband transversal equalizer is shown in Fig. 3. Also shown are circuit blocks for carrier recovery and timing recovery, which could derive their inputs from the places shown or from other signal points in the receiver. These are critical receiver functions and, particularly in a complex fading environment, are interactive with each other and with the equalization strategy. These and the other adaptive techniques used in digital radio receivers will be discussed in the fourth paper of this series [14].

A system designer armed with knowledge of possible modulations, statistical channel models, and adaptive receiver techniques is in a good position to estimate

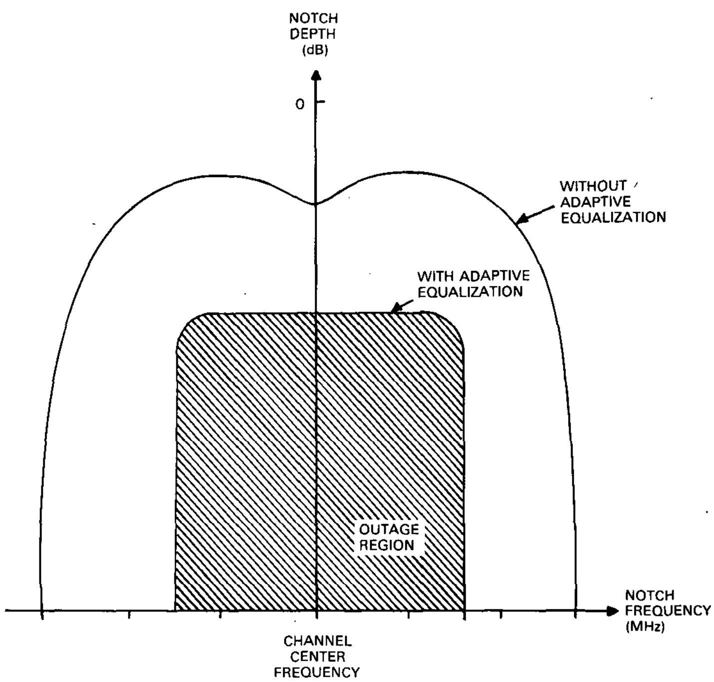

Fig. 2. Equipment signature curves.

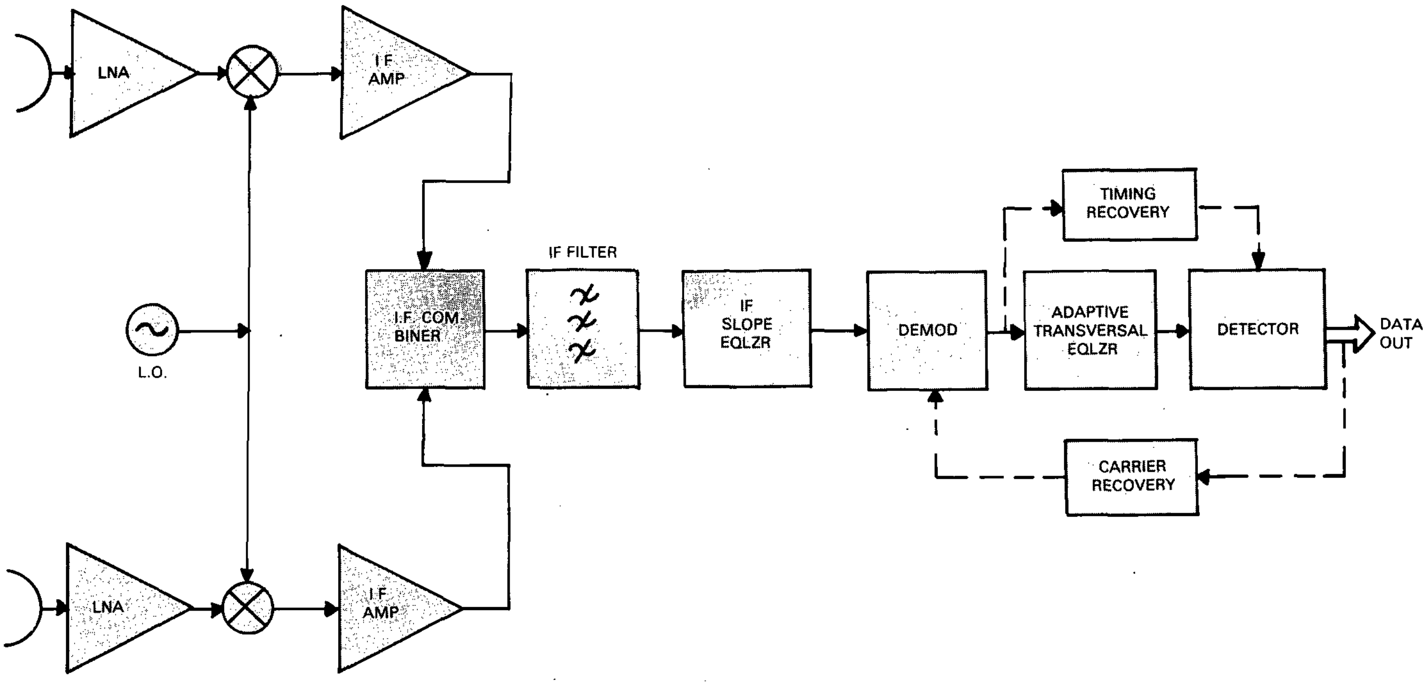

Fig. 3. Space diversity receiver.

outage time, the expected number of seconds in a year for which outage will occur on a given link. The development of analytical/computational methods for outage time estimation (some of which are based on the use of signatures such as those shown in Fig. 2) has engaged many workers in the field (cf [15,16]). The fifth paper of this series will discuss outage prediction techniques and their relationship to the statistical behavior of the fading channel [17].

Equipment Requirements

Essentially, the equipment problems encountered in modern digital radio arise because of the need, amidst propagation anomalies, to transmit high-level modulations. We have seen that a digital radio system must achieve a spectral efficiency of 4.5 bits/sec/Hz in the 4-GHz band in order to provide a capacity of 1344 voice circuits. However, practical QPSK modulations can only achieve an efficiency somewhat below 2 bits/sec/Hz. It is thus clear that, to achieve the required efficiency, modulation formats that carry more than two information bits per channel symbol must be used. At the present stage of development, digital radios in the 4- and 6-GHz bands are, in fact, achieving spectral efficiencies of 4.5 bits/sec/Hz (cf [18]).

From the earliest days of digital radio, linear modulation formats have been employed almost exclusively. Thus, regardless of the number of modulation levels, the modulator and demodulator can always be modeled as a form of QAM. A general block diagram of a quadrature amlplitude modulator is shown in Fig. 4. We see that a pair of quadrature-phased carrier signals are each modulated with a discrete number of information levels per symbol period and then summed to form the QAM signal. For example, in 16-QAM, each carrier is modulated by one of four discrete levels (corresponding to two information bits), so that, in each symbol period, the resulting modulated signal has 16 possible variations and carries four information bits. The demodulation of such a signal in the receiver essentially reverses the sequence of operations: IF filtering, balanced demodulation using two quadrature-phased (IF) carriers, baseband filtering, and A/D conversion (detection).

As the number of modulation levels increases, so does the sensitivity of the resulting signal to equipment imperfections and impairments. For example, for a higher number of modulation levels, noise margins (and, hence, signal robustness) decrease. The result is that an equalizer must compensate for selective fading more accurately and to a greater degree.

In addition, high-level modulations require highly accurate carrier and timing recovery circuits, since the potential for intersymbol interference is greater for such signals. These synchronization schemes pose a complex design problem and, because of the interdependencies of carrier recovery, timing recovery, and data equalization, often must be decision-aided loop structures [12,19,20].

When high-level modulations are employed, system performance becomes increasingly sensitive to linear distortions in the transmission equipment. To a large extent, these distortions appear as asymmetries in the amplitude responses and variations in the group delay characteristics of the filters in the transmission path. In order to avoid overloading the adaptive equalizer in the receiver, it is therefore of importance that all filters in both the transmitter and receiver be equalized. In particular, they should have essentially symmetric amplitude responses and flat group delay character-

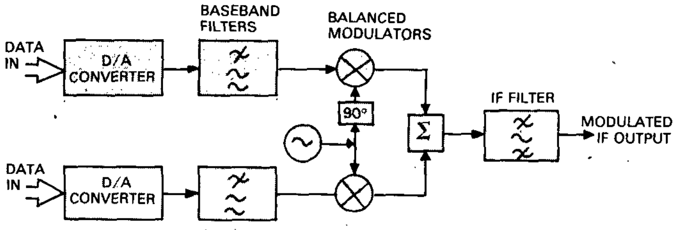

Fig. 4. Quadrature amplitude modulator.

istics, at least within the passband of the signal. This necessity complicates both the design and the implementation of the required filters.

Finally, the high-level modulations used in modern digital radio systems have many amplitude levels and correspondingly high peak-to-average power ratios. Because of this, they are very sensitive to nonlinear distortion, and this sensitivity increases with the number of modulation levels. Nonlinearity may occur in any active component of either the transmitter or receiver. However, the primary source of degradation, and therefore the chief concern of the system designer, is the power amplifier (PA) at the output of the transmitter.

Most digital radio routes consist of a chain of regenerative repeaters, each containing a PA. These devices operate most efficiently when close to their saturation points, where they cause significant nonlinear distortion. To minimize this problem, it is necessary either to operate the PA at a large backoff from saturation, or to provide some means of nonlinearity compensation (for example, linearizing the amplifier or predistorting the signal so that it becomes insensitive to the nonlinear effects). From the standpoint of repeater power efficiency, the latter is the more attractive approach, and a number of compensation schemes have been investigated [21,22]. These allow the PA to operate at or near saturation with a significant increase in power efficiency—an important consideration in remotely sited repeaters which rely on local power generation.

Current and New Systems

We now briefly cite some of the major digital radio systems in use today. In North America, there are common-carrier frequency allocations at 2, 4, 6, and 11 GHz, with an additional allocation at 8 GHz in Canada. In addition, there are allocations at 2, 6, and 12 GHz for industrial private networks. Common carrier designs have now been essentially standardized, so that the 4-GHz systems can carry two DS-3 streams per 20-MHz channel; the 6-GHz and 11-GHz systems carry three DS-3's in 29.65-MHz and 40-MHz channels, respectively; and the 8-GHz systems carry two DS-3's in a 40-MHz channel. In Canada, there is a long-haul system at 8 GHz which spans the entire country, and in the United States, there are over 10,000 digital radio links in use in the telephone network, including both short- and medium-haul systems [23]. Cross-country (long-haul) networks at 4 GHz are now nearing completion in the United States.

In Japan, there is currently an extensive network of digital radios in use in the 2-, 4/5-, 11/15-, and 20-GHz bands, at data rates ranging from 3 Mb/s to 400 Mb/s per radio channel. The status of development and deployment of these is described in some detail in [24]. Most of the currently deployed radios utilize 4-PSK, 8-PSK, or 16-QAM. However, planning and development of 64- and 256-QAM radios is actively underway. In fact, by the year 2000, the Japanese expect to have an essentially completely digital telecommunications network, in which it is expected that high-capacity digital radio will play an important role.

In Australia and New Zealand, developments are also proceeding rapidly. In most instances, 140-Mb/s systems employing 16-QAM are being developed and deployed. However, some work is in progress on more efficient modulations, such as reduced bandwidth QPSK [25] and very high-level QAM.

In Europe, the 4-GHz band has been rechannelized to 40-MHz bandwidths, and 140-Mb/s systems are now being deployed in the 4-GHz and upper 6-GHz bands. Additional planning and deployment are underway at 11 GHz and 18 GHz.

Conclusions and Future Trends

There is now a great deal of activity worldwide on the development of high-capacity digital radio systems. While much of this activity is going on in research laboratories, we are also seeing the deployment in the field of a large number of systems of increasing capacity, sophistication, and reliability. The question naturally arises as to what the future holds, and this will be discussed in some detail in the sixth and final paper of this series [26]. We close this introductory paper by briefly speculating on some of the possibilities.

It seems at this point that most of the developments will lie in the areas of (1) increasing the reliability of transmission, and (2) increasing the efficiency of use of the available radio spectrum. Increased transmission reliability can be achieved through more sophisticated equalization and diversity strategies. It can also be increased through the use of *forward error correction* (FEC) coding techniques and more robust modulation techniques. As VLSI implementations of error-correction decoders become available at the required signaling rates, it seems likely that the use of FEC coding will increase. Also, improved equipment reliability is anticipated from the increased use of monolithic microwave integrated circuits, VLSI, and other microwave techniques, such as dielectric resonators and solid-state amplifiers.

Increased efficiency of use of the available spectrum can be achieved through the use of still higher levels of modulation and through frequency reuse. From the above discussion, it is clear that higher-level modulations are being actively pursued. There is also significant research going on to increase capacity through the use of orthogonal polarizations (dual-polarization transmission) and through the development of technologies for higher frequency bands.

It is extremely difficult to forecast where these investigations will lead. However, it is safe to say that the next few years will bring continued rapid growth and development in the use of high-capacity digital radio systems.

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