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Land Mobile Radio Systems - A Tutorial Exposition

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An in-depth tutorial on land mobile radio systems

Mobile Radio Channel Characteristics

IN MOBILE RADIO SYSTEMS, the propagation between the transmitting antenna and the mobile unit antenna is over several paths, namely, the line of sight path and the paths due to scattering caused by reflections from and diffractions around obstructions. These interfering signals produce a complex standing-wave pattern of varying field strength, with maxima and minima being of the order of a quarter wavelength apart. As a result of the vehicle movement through this standing wave pattern, the received signal experiences random variations in both amplitude and phase. Fades of 40dB or more below the mean signal level are common, with successive minima occurring about every half wavelength of the carrier transmission frequency. The received signal fluctuates as the vehicle moves, thus distorting speech when transmitted by conventional methods.

Starting from a model based on multipath wave interference arising from multiple scattering of the waves by buildings and other structures in the vicinity of the mobile unit, Clarke [1] and Gans [2] have shown that the envelope of the mobile radio signal is Rayleigh distributed when measured over distances of a few tens of wavelengths, where the mean signal is sensibly constant, whereas, the phase of the received signal is uniformly distributed from 0 to 2π. Therefore, the probability density function of the received signal envelope S relative to the local mean $\overline{a} = E(S)$, can be written as:

$$P(S/\overline{a}) = \frac{\pi S}{2\,\overline{a}^2} \exp\left(-\frac{\pi S^2}{4\,\overline{a}^2}\right), \qquad S > 0$$

Although the statistics of the received signal envelope are Rayleigh distributed, the local-mean $\overline{a}$ varies typically between 6 to 12 dB due to shadowing. Shadowing of the radio signal by buildings and hills leads to a gradual change in the local-mean which can be characterized statistically by log-normal distribution [3] with two parameters (m_d, σ). The log-normal distribution with parameters (m_d, σ) in dB is described by the probability density function:

$$P(\overline{a}) = \frac{K}{\overline{a}\,\sigma} \exp\left(-\frac{1}{2\sigma^2}\{20 \log_{10} \overline{a} - m_d\}^2\right)$$

where K is a constant, m_d and σ^2 are the mean and variance of the corresponding normal distribution.

The probability density function of the signal envelope under Rayleigh fading and log-normal shadowing has been derived in [4] and it is given by:

$$P(S) = \frac{k}{\sigma}\int_{-\infty}^{\infty} \frac{S}{10^{a/10}} \exp\left[-\frac{\pi S^2}{4\times 10^{a/10}}\right] \exp\left[-\frac{(a-m_d)^2}{2\sigma^2}\right] d\sigma$$

where k is a constant, and $a = 20 \log_{10} \overline{a}$

The expected rate at which the envelope crosses a specified value R, can be obtained using [5]:

$$N_R = \int_0^{\infty} \dot{S}\, P(R,\dot{S})\, d\dot{S}$$

where N_R is the level crossing rate, $\dot{S}$ is the time derivative of the envelope amplitude S, and $P(R,\dot{S})$ is the joint density function of the signal envelope at $S = R$ and $\dot{S}$. It has been shown (for Rayleigh fading only) [3] that the deeper the fade, the less frequently it is expected to occur. The average duration of fade is defined as:

$$\overline{\tau} = \frac{P(S \leq R)}{N_R}$$

Both the rate N_R and the average duration $\overline{\tau}$ of the fades are useful in the evaluation of the receiver performance.

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Besides the random variations in signal amplitude and its phase, each component plane wave has a Doppler shift associated with it depending on the mobile speed, the carrier frequency, and the angle its propagation vector makes with the mobile velocity vector.

$$f_D = \frac{v}{\lambda} \cos \alpha$$

where $\frac{v}{\lambda}$ is the maximum Doppler shift ($\alpha = 0$) at the carrier wavelength λ, and v is the vehicle speed.

The signal power falls off (attenuates) rapidly as the vehicle moves away from the base station. Attenuation of the signal power with distance changes from an inverse cubic law to an inverse fourth power law. The received signal power is a function of base station and mobile unit antennas height, separation between the two antennas, transmission frequency, width and orientation of the streets in urban areas, and atmospheric conditions. Described below are some of the parameters that are useful in the evaluation of channel characteristics.

Coherence Distance

This is the minimum distance between two points for which the signals are not strongly correlated, that is with a correlation coefficient of less than 0.5 [3]. The coherence distance is typically of the order of one-half wavelength in an urban location. This property of the channel enables space diversity to be used in order to combat the effects of Rayleigh fading.

Coherence Bandwidth

The different path lengths for the received signal give rise to different propagation time delay, typical spreads in time delays range from a fraction of a microsecond to many microseconds, depending on the type of environment. The existence of the different time delays in the various waves that make up the total field, causes the statistical properties of two signals of different frequencies to become essentially independent if the frequency separation is large enough. The coherence bandwidth B_c is defined [6] as the frequency spacing between two signals with a correlation coefficient of 0.5 or less. B_c is typically from 30 kHz to 1 mHz. The frequency selective properties of mobile radio channel make it possible for some system plans to employ frequency diversity in order to combat the effects of fading.

Coherence Time

The difference in time between two samples of the signal with a correlation coefficient of 0.5 is termed the coherence time of the channel. A typical value of T_c is 1.3 ms or more. The frequency dispersive properties of the channel can be utilized in a time diversity scheme to combat the effect of fading.

The next section discusses the concepts of cellular systems and how they could provide effective service to mobile users.

Cellular Systems

A spectrum efficient high-capacity system with a flexibility to accommodate the increased user densities, called the "Advanced Mobile Phone Service" system, has been studied by MacDonald [7]. The service trial of the Advanced Mobile Phone Service (AMPS) was begun in the Chicago area in 1979. The system objectives are [8]:

1) Large subscriber capacity
2) Efficient use of the spectrum
3) Nationwide compatibility
4) Widespread availability
5) Adaptability to traffic density
6) Service to vehicles and portables
7) Regular telephone service and special services, including dispatch
8) High quality of service and affordability

Frequency reuse and cell splitting summarize the essential features of the cellular concept.

Basics of the Cellular Concept

The total coverage area is divided into interlocking polygons called a cell. Each one contains its own land radio equipment for transmission to and reception from mobile units within the cell. A cellular system could be designed with square or equilateral triangular cells, but for economic reasons, the regular hexagonal shape has been adopted for Advanced Mobile Phone Service (Fig. 1). Each cell is served by a base station located at the center of the cell or at the alternate corners of the hexagons. In the first case, the cell site base station employs omnidirectional antennas to communicate with the surrounding mobiles, while in the second case the cell site uses directional antennas with 120° beamwidth to illuminate portions of the three adjacent cells which meet at the cell site. The center-located cell concept is likely to be applied in small cities because it has the economic advantage of requiring fewer cell sites. However, in large high rise cities, the corner excitation arrangement is more practical because it gives a form of space diversity that could improve the system performance in the presence of lognormal shadowing.

A fixed number of radio channels are allocated to each cell. Since each base station provides coverage only over one cell, the group of channels allocated to a cell can be used by another cell when the two are suitably separated geographically. This is called the frequency reuse which is the second essential feature of the cellular concept. The idea of employing frequency reuse in mobile-telephone service on a shrunken geographical scale hints at the cellular concept. Instead of covering an entire local area from one land transmitter site with high power at a high elevation, the service provider can distribute transmitters of moderate power throughout the coverage area, thus, increasing the system

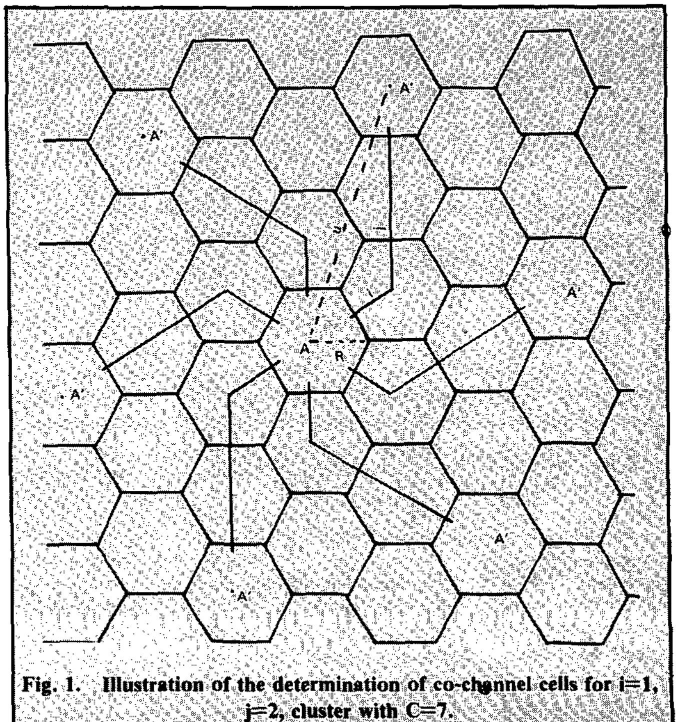


Fig. 1. Illustration of the determination of co-channel cells for i=1, j=2, cluster with C=7.

capacity. This frequency reuse causes co-channel interference, since the terrain or buildings in the vicinity of the mobile or the cell sites can cause a receiver to block a transmitter in a more distant cell site. In order to control this effect and to evaluate the system performance, we define the reuse distance ratio D as "the ratio of the distance between cell sites that use the same channels to the cell's radius," Fig. 1, where D as a function of co-channel interference has been evaluated [10–11]. The results which have been obtained in [11] reveal that to avoid high levels of co-channel interference it is necessary to use large D.

The cells form a natural block or cluster around the reference cell in the center and around each of its co-channel cells. The exact shape of a valid cluster is not unique, all that is required is that it contains exactly one cell with each label. Figure 1 shows a cluster with $C = 7$. The number of channels in each cell, $N_S = \frac{N_t}{C}$, where N_t is the total number of channels available for the system, and C is the cluster size given by:

$$C = (i + j)^2 - ij$$

Here, i and j are positive integers including zero.

Initially, a fixed number of channels N_S per cell are allocated. As the suburban areas surrounding the metropolitan centers grow, more hexagonal cells can be appended to the initial system. When the users' density in the metropolitan center increases and more channels than N_S are required, the cells are divided into smaller cells and the minimum reuse distance, D, which provide low level of interference is maintained. This process is called "cell splitting." Ideally, if N_S is of reasonable size to start with, no further allocation is needed as demand increases.

System Description

Communication to and from any mobile unit is made via the base station serving the cell in which the mobile unit is located. Each base station "cell site" is equipped with a controller that performs call set up, call supervision, mobile location [12], handoffs, and call termination. All base stations are connected (via wire lines) to and controlled by a central Mobile Telephone Switching Office (MTSO) which serves as a routing center, that is, mobile location and handoffs when the mobile moves from one cell to another, Fig. 2. A processor within each mobile conducts the signaling, radio control, and customer alerting functions.

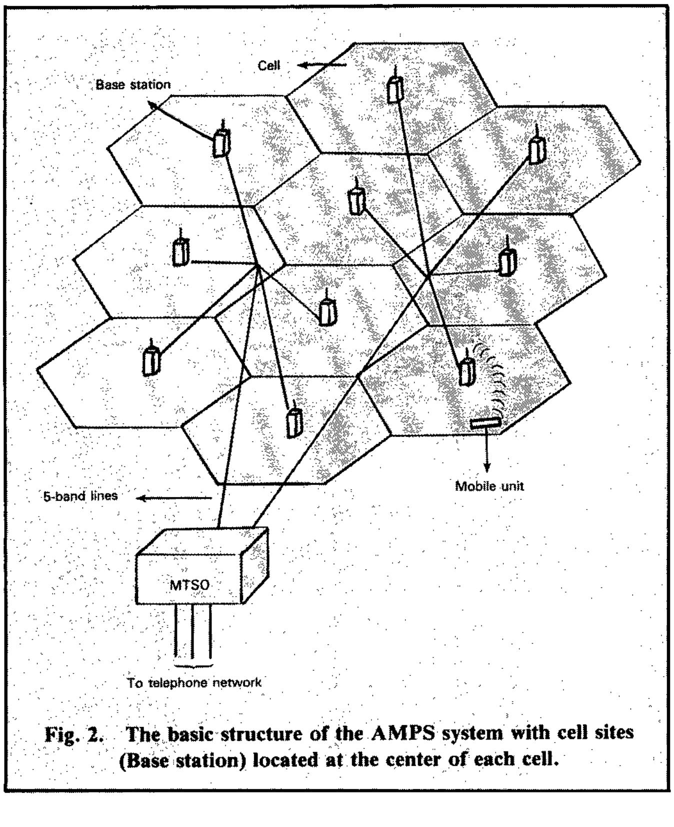


Fig. 2. The basic structure of the AMPS system with cell sites (Base station) located at the center of each cell.

Radio communication in AMPS employs frequency modulation. Transmission from mobiles to cell sites uses channel frequencies between 825 and 845 MHz, and from cell sites to the mobiles, frequencies between 870 and 890 MHz are used. Each band is then divided into narrow band (30 KHz bandwidth) channels, and communication is effected using channel-pair per cell.

Two types of radio channels are required. One type is called the set up channel. Set up channels transmit and receive only binary data messages. They are the common use channels and are monitored by mobiles which do not have an active call in progress. They are used only for initiating or setting up phone calls. The second type is called the voice channel, which provides the talking path for the customers and also handles short bursts of data that may be required for control purposes during the call.

When the mobile radio unit crosses the cell boundary the MTSO must re-route the call, and also an idle channel-pair in the new call must be found. If no channels are available in the new cell, the call is permitted to degrade until a channel is available.

Channel Assignment in Cellular System

In a cellular mobile radio system, the number of channels in each cell is determined by the user density, the frequency reuse distance D (to produce an acceptable co-channel interference), and the available bandwidth. After a base station has been assigned to serve the mobile radio unit, a channel assignment procedure must be followed to determine if a channel is available or not.

In a fixed channel assignment [13] scheme, a subset of the total available channels is permanently assigned to serve a certain cell. The channel subsets are reused in the coverage area separated by a reuse distance. Only channels from this subset can be used to serve a call within the cell. If all the channels in this subset are busy, then service cannot be provided (blocked call) even though there may be vacant channels among those which are assigned to serve in adjacent cells.

In dynamic channel assignment scheme [13–15] all channels are kept in a central pool, and any channel can be used in any coverage area "cell." In order to avoid a high level of co-channel interference, a channel can be reused simultaneously in another cell if they are separated by D. Control of a dynamic channel assignment system requires access to and processing large quantities of data; a fast digital computer is required. Channels are assigned to serve calls based on the state of the system and in order to optimize some parameter within the system, different channel borrowing strategies have been proposed and simulated [13,16]. In Hybrid Channel Assignment, the total number of channels available for the entire system is divided into two groups. One group contains channels using the Fixed Channel Assignment scheme, the other group contains channels using the Dynamic Channel Assignment scheme. Simulation study has been carried out [17], to investigate in what ratio the channels should be divided. It was found that the optimum ratio depends on the percentage increase in the traffic density.

A channel assignment that reduces the co-channel interference, spurious, and intermodulation was proposed by Box [19]. A new channel assignment scheme has been proposed and simulated in [20]. This scheme uses a flexible fixed channel assignment with borrowing and channel reassignment in such a way as to minimize the blocking probability. The results reveal that such strategy has a better performance than other known assignments.

In the next section we shall discuss some of the diversity techniques useful in improving the communication in mobile radio.

Diversity Techniques for Land Mobile Radio

Different types of diversity, such as space diversity, frequency diversity, polarization and angle diversities, and time diversity, can be used to improve the performance of communication systems. (Diversity in land mobile radio is used to combat the effect of Rayleigh fading signal discussed earlier.)

Time diversity, as the name suggests, involves the repetition of messages and hence, delays the effective information transfer. Sequential amplitude samples of a randomly fading signal, if separated sufficiently in time, will be uncorrelated with each other and therefore, the samples provide "independent information." However, the minimum time separation between samples is inversely proportional to the speed of the vehicle. In other words, for the stationary vehicle, the time diversity is useless. Even though the delay can be tolerated, the above fundamental limitation rules out time diversity for mobile radio. Perhaps space and frequency diversity are the best applicable.

Space diversity has the advantage that it does not need additional spectrum. The basic requirement is that the spacing of the antennas in the receiving or transmitting array be chosen so that the individual signals are at least partially uncorrelated. Recalling the discussion on channel characteristics, we see that the antenna spacing of roughly one half wavelength could be sufficient. At 850 MHz, this means a fraction of a meter separation, which can be achieved in mobiles. However, for diversity at the base station, since the important scatterers are in the immediate vicinity of the mobile, the base station antennas must be considerably farther apart to achieve decorrelation. Separation of the order of tens of wavelengths would probably be adequate at the base station [21]. We shall subsequently discuss some of the combining schemes.

Instead of transmitting the desired message over spatially separated paths, as described in space diversity, one can employ different frequencies to achieve independent diversity branches. The frequencies must be separated enough so that the fading associated with different frequencies is uncorrelated. If the spacing between the carriers is sufficiently larger than the coherence bandwidth, then independent fading of the two signals can be expected. The price paid is increased spectrum usage. However, by use of spread spectrum concepts, it may be possible to achieve "frequency diversity" without the loss of spectral efficiency.

Specific Space Diversity Combining Techniques for Mobile Radio

Selection diversity—this is perhaps the simplest technique of all. Referring to Fig. 3, we see that one of the M receivers having the highest baseband SNR is connected to the output. As far as the statistics of the output signal are concerned, it is

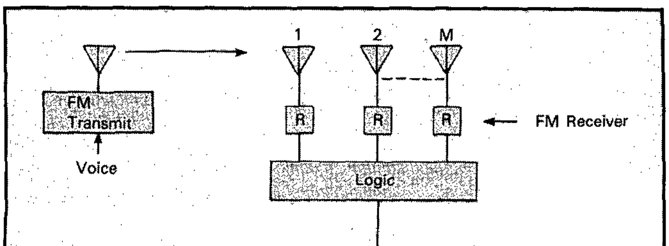


Fig. 3. Principles of selection combining.

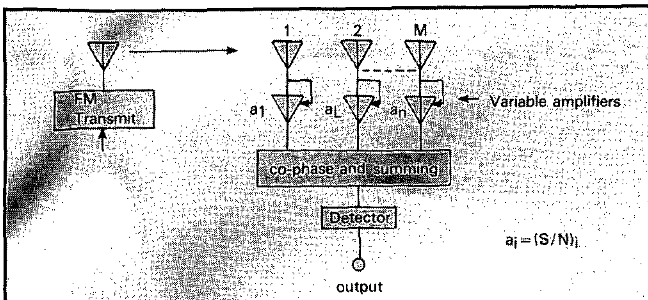


Fig. 4. Principles of maximal ratio combining.

immaterial where (*IF* or *RF* or at the antennas) the selection is done. Two branch diversity can improve the signal level by 10 dB at the 99 percent reliability level (called the diversity gain); four-branch diversity yields 16dB diversity gain.

Maximal ratio combining—here the M signals are weighted proportionally to their individual signal voltage-to-noise power ratios and then summed. Figure 4 shows the essentials of the method. The individual signals must be co-phased before combining, in contrast to selection diversity. This kind of combining gives the best statistical reduction of fading of any known linear diversity combiner. A two branch diversity gain of up to 11.5 dB gain at 99 percent reliability level can be achieved, and four branches can give 19 dB gain. It may now always be convenient or desirable to provide the variable weighting capability required for true maximal ratio combining. Instead, the gains may all be set equal to a constant value of unity, and "equal gain combining" results. This is only a fraction of a decibel poorer than maximal ratio.

The AMPS system can use space diversity at both ends (see voice and data transmission) although mobile manufacturers typically do not yet offer diversity at the mobiles. Improved systems, with many branch space diversities are under investigation [57,58].

Spectrum-Efficient Technology for Mobile Radio

With the availability of 40 MHz in the 800 MHz band for land-mobile radio, the interest focused on the effective utilization of the frequency spectrum, that is accommodating the maximum number of users in a given geometrical location, within the available bandwidth and at a reasonable cost. While three possible methods have been proposed, no clear-cut decision on any method taking into consideration all the aspects, could be made yet. In [22–23] possibility of a single side band (SSB) amplitude modulation transmission to replace the existing FM mobile radio was discussed. Though the author has predicted seven to ten times increased spectrum-utilization over FM, later reports [24] raised doubts about the suitability of SSB as an alternative. The motivation to use SSB is due to the fact that the modulated SSB signal occupies less bandwidth than a narrow band FM signal.

Another possibility is to reduce the channel spacing to 12.5 KHz in an FM system. Finally, there's the possibility of spread-spectrum modulation. At first, someone could wonder how the spreading of bandwidth occupied by a user could lead to increased spectral efficiency. In fact, it is possible to reduce the interference among the users by properly spreading the transmitted energy, thereby accommodating many users over a given bandwidth, as will be seen in the next section.

Spread Spectrum for Mobile Radio

The first attempt to introduce spread spectrum as a spectrally efficient scheme for mobile radio appeared with the proposal of

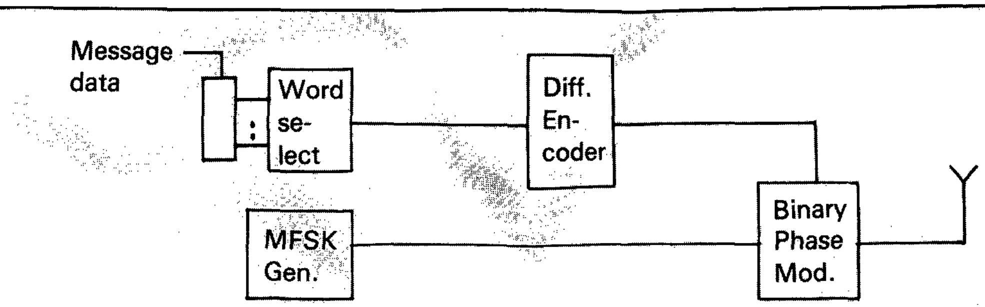


Fig. 5. Transmitter in FH-DPSK system.

a Frequency Hopped-Differential Phased Shift Keyed system (FH-DPSK) [25,27]. Generally, a direct sequence spread spectrum system performs very poorly under multi-user interference and fading channels [28]. Frequency hopping (FH) schemes possess inherent capability to provide diversity against frequency-selective fading encountered in mobile channel. Henceforth, we shall consider only the FH schemes. Some of the advantages of the spread spectrum which are not easily achievable with other systems are summarized in [25]. With spread spectrum, the questionable cost effectiveness and the formidable technological problems in the implementation remains to be answered [26].

A preliminary analysis of FH systems [27,29,30] shows that these systems could be spectrally more efficient than the conventional FM systems. Another analysis of the FM system with several branch diversities indicates that this system could be more efficient spectrally than the FH systems. However, all these studies do not take into account all the relevant mobile radio conditions, and until experimental results and further analytical work are made available, no decisive choice could be made. An alternative to FH-DPSK is the Frequency Hopped Frequency Shift Keying (FH-FSK) and this has been shown to accommodate more simultaneous users than the former scheme. In the following paragraphs, we shall discuss these two systems and summarize the available results.

FH-DPSK System [25,27]

Transmitter

A block diagram of the FH-DPSK transmitter is shown in Fig. 5. There are two parts to the modulation process in the transmitter: addressing and encoding. Addressing is performed by the MFSK generator, which repeats with period T a specific sequence of N different tones or chips, each of duration t_1 ($t_1 = T/N$). The specific sequence is generated according to an assigned address to the user and each user is assigned an address which is distinguishable from others despite overlap in some positions. Each mobile is fitted with a transmitter of the kind described and with a receiver to be described. The power radiated from each mobile is remotely controlled from the base station to ensure that all the signals arriving at the base station are nearly of equal strength. If this is not done, mobiles close to the base station will swamp the signals of those further away. This is the "near-far" problem common to most spread spectrum systems.

Signal information is impressed or encoded onto the MFSK address sequence in the form of binary differential phase shift keying. If a binary-1 is to be transmitted in the i^{th} chip of the address sequence, the phase of that chip is changed by π radians relative to the phase in the i^{th} chip of the previous sequence. For a binary +1, no phase change takes place. In order to increase the resistance of this type of modulation to interference, the allowed phase modulation sequences or words are selected from a set of N orthogonal words, such as the columns of Hadamard matrix [31].

Receiver

A block diagram of a typical receiver is shown in Fig. 6. There are N sections each with a band pass filter, delay element, product detector, and a low pass filter. Each section is typical of a receiver used to detect DPSK signals [32]. The array of t_1 second delay lines and the set of N band pass filters selects the desired address waveform out of the incoming signal. In other words, the band pass filter center frequencies ($\omega_1 \ldots \omega_N$) are uniquely related to the address of the user under consideration. Each band pass filter is matched to rectangular chip of duration t_1 and therefore, has a noise bandwidth of $1/t_1$. All N chips pass through the filters at the same time and

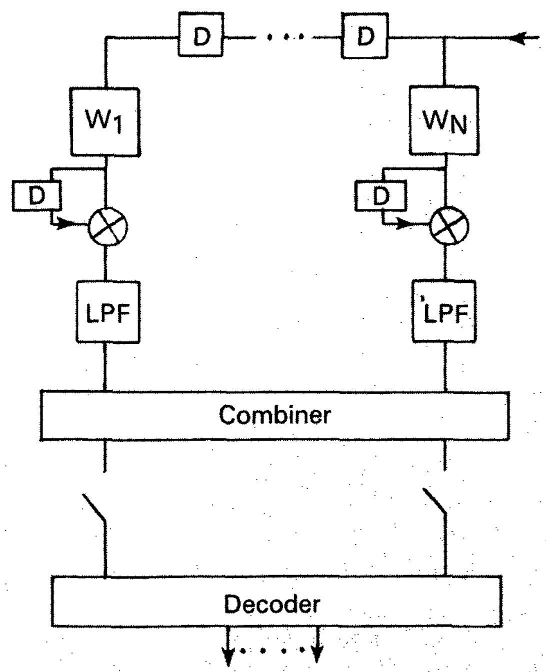


Fig. 6. Receiver in FH-DPSK system.

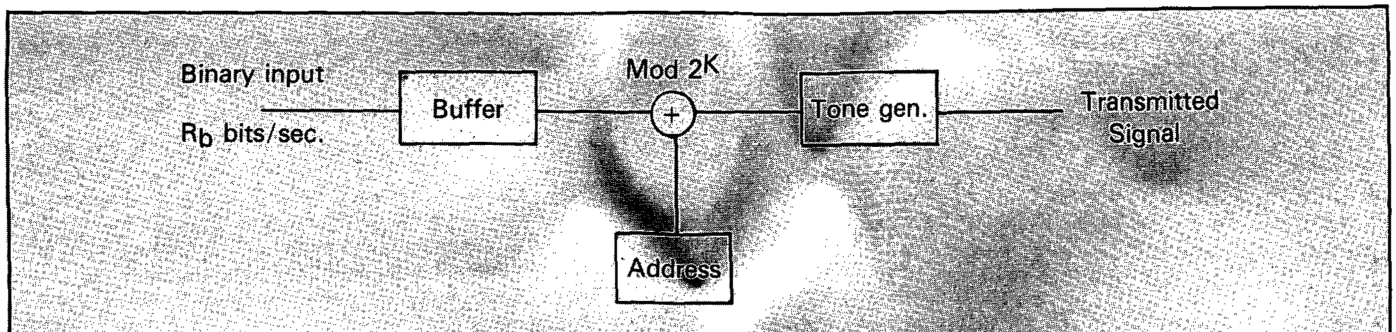


Fig. 7. Transmitter in FH-MFSK.

their phases (relative to the previous word) are detected using the T sec. delay element and the product detectors. After low pass filtering to remove the second harmonic product terms, the detector outputs are processed in a combiner circuit.

Combiner Circuits

Denoting the outputs of low pass filters as X_ℓ, $\ell = 1,\ldots N$ and the outputs of combiner as C_k, $k=1, \ldots N$ we can express C_k's as:

$$c_k = \sum_{\ell=1}^{N} h_{k\ell} X_\ell$$

where $h_{k\ell}$ are the elements of $N \times N$ Hadamard matrix. Due to channel characteristics the possibility of a word detection error arises. It turns out that the linear combiner (above) is not the best to use in order to minimize the probability of error. When X_ℓ can be statistically characterized under Rayleigh fading and with some interference models, it is possible to apply hypothesis testing to determine the correct word. This leads to a likelihood receiver, which is the best in the sense of minimizing the probability of bit error, with the available information [33].

For successful operation of FH-DPSK under multi-user environment, we need to assign addresses that possess certain properties. Since transmission from the mobile units to the base stations are to be non-synchronous (which is advantageous), it is desirable to use signal sets that have uniformly small cross-correlation functions for any relative time shift. A class of time frequency coded signal with the one-coincidence property is suitable for the purpose [25].

Assuming ideal conditions, that is no fading, no receiver noise and perfect synchronization, Rowe has derived upper bounds on the active users U for the best possible signal set as functions of W, R_b, alphabet size, and P_b [36]. Whereas these results do not correspond to actual conditions, they predict the best that is possible under ideal situations. In [37] an upper bound on number of vectors (this when divided by number of vectors per user gives the number of users) possible on d dimensional space (here $d = 2TW$) is obtained, given some suitably defined root-mean square cross correlation C_{rms}.

Performance Analysis of FH DPSK System

The maximum number of simultaneous users that could be accommodated at a specific bit error rate is of interest in analyzing a digital mobile radio system. Since this number could vary depending on the available bandwidth or on the information bit rate, a measure defined as "spectral efficiency" is also useful:

$$\eta = \frac{M\,R_b}{W}$$

where η is spectrum-efficiency, M is the number of users simultaneously served by the system, R_b is the bit rate per user, and W is the one-way bandwidth.

We shall discuss later the merit of η as a measure of spectral-efficiency in a larger context of the efficient utilization of the spectrum allocated for land-mobile users. Presently, η can be used to compare two cellular systems. A comparison of average number of usable "channels" per cell for FH-DPSK and FM systems showed that they do not differ greatly. In [38], it is noted that no error occurs if the transmission is frame synchronous (which is possible for base to mobile communications), and for frame-asynchronous mobile to base communications, a good estimate of P_b was arrived at. The analysis showed that only 26 users can be accommodated at $P_b < 10^{-3}$ and at large E_b/N_o with $W = 20$ MHz, $R_b = 32$ kb/s, and orthogonal coding rate $\lambda = 5/32$ ($= \log_2 N/N$). This figure improved to $M = 46$ from 26 by the use of hard-limited combing [34]. However, likelihood combining did not give any further significant improvement [33]. Another analysis of P_b with different models of fading for the envelope of received signal was carried out in [39]. In all the above analyses, shadow fading was neglected. Also, the assumption was made that the frequency separation between the spectrum of the hopping signals was greater than the coherent bandwidth of the mobile channel. Even though this gives the full benefit of diversity and makes the analysis simpler, this may not be strictly valid [40].

Next, we shall discuss another FH scheme which is more efficient than FH-DPSK.

Frequency-Hopping Multi-Level Frequency-Shift Keyed System (FH-MFSK)

A block diagram of the m[th] transmitter of FH-MFSK system is shown in Fig. 7. Figure 8 shows the block diagram of the receiver. The operation of the system can be understood by referring to Fig. 7, and Fig. 8. Every T seconds, K message bits are loaded serially in a buffer and transferred out as a K-bit word X_m. Assuming the modulo-2^K adder does nothing for the moment, X_m will select one of the 2^K possible different

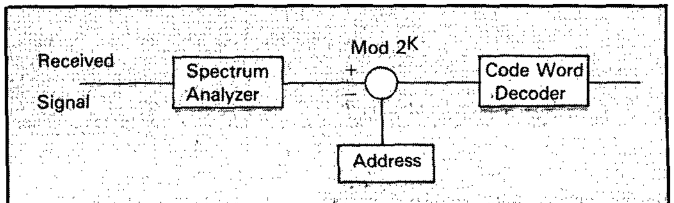


Fig. 8. Receiver in FH-MFSK.

frequencies from the tone generator. At the receiver, the spectrum of each T second transmission is analyzed to determine which frequency, and hence, which K-bit word, X_n is sent. Of course, the system as such is useless for multiple-user operation. If a second transmitter were to generate X_n, neither the receiver m nor the receiver n would know whether to detect X_n or X_m. To avoid this, we add the address generator as shown in Fig. 7 and assign a unique address to each user.

The basic interval T is divided into L intervals of duration τ each. Over T seconds, the address generator of m^{th} user generates a sequence of L numbers:

$$a_m = (a_{m1}, a_{m2}, \dots a_{mL})$$

$$\textit{Each } a_{mi} \in \{0, 1, 2, \dots 2^K - 1\}$$

whereas in [30] each a_{mi} is selected at random from the set specified above (called "random address assignment"). There are certain addressing schemes [41,42] which possess certain algebraic structure and hence, when decoded at the receiver properly, could lead to better performance.

Now, each $a_{m\ell}$ is added modulo-2^K to X_m to produce a new K-bit number:

$$Y_{m,\ell} = X_m + a_{m\ell}$$

or,

$$\underline{Y} = (Y_{m1}, Y_{m2}, \dots Y_{mL})$$

$$\underline{X_m} = (X_m, X_m, \dots X_m)$$

$$\underline{Y} = \underline{X_m} + \underline{a_m}$$

Each τ seconds, $Y_{m\ell}$ selects the corresponding transmitter frequency. At the receiver, demodulation and modulo 2^K subtraction by the same number $a_{m\ell}$ are performed every τ seconds, yielding:

$$Z_{m\ell} = Y_{m\ell} - a_{m\ell} = X_m$$

The sequence of operations is illustrated by the matrices of Fig. 9a and 9b. Each matrix is either a sequence of K-bit numbers (codeword, address, detection matrix) or a frequence-time spectrogram (transmit spectrum, receive spectrum). The matrices pertain to one link in a multi-user system. Crosses show numbers and frequencies generated in that link. Circles show the contributions of another link. As stated earlier, the transmit spectrum is generated by modulating the address with a code word using modulo-2^K addition. Equivalently, when each entry in the address matrix is shifted cyclically by the row number specified by the codeword matrix, we get the transmit spectrum (Fig. 9a).

Because of multi-users, extraneous entries are created in the detection matrix. For example, a word X_n transmitted over the n^{th} link will be decoded by the receiver m as:

$$Z'_{m\ell} = X_n + a_{n\ell} - a_{m\ell}$$

The $Z'_{m\ell}$ are scattered over different rows. The desired transmission, on the other hand, is readily identified because it produces a complete row of entries in the detection matrix. Normally, the fading of the tones and the receiver noise can cause a tone to be detected when none has been transmitted (false alarm) and/or can cause a transmitted tone to be undetected (miss). Even without these impairments, many user entries can combine to produce a complete row other than X_m and hence, can cause errors in the identification of a correct row (in the word X_m). Hence, a majority logic rule is attempted: select the codeword associated with the row containing the greatest number of entries. Under this decision rule, an error will occur when insertions (detected tones due to other users and false alarms) combine to form a row with more entries than the row corresponding to the transmitted code word. An error can occur when insertions combine to form a row containing the same number of entries as the row corresponding to the transmitted code word. We view the transmission to each square in the tone detection matrix as an example of non-coherent, on-off keying. Because of fading of amplitude and the random change of phase, it is not possible to employ coherent detection in a mobile environment. (Recall that we used differential phase detection in FH-DPSK scheme, since the phase is not likely to change significantly from bit to bit [25].) From the textbook formulas we have [43]:

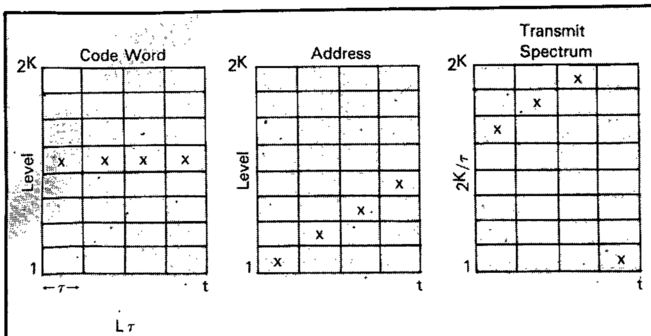


Fig. 9a. Matrices in Transmit Portion.

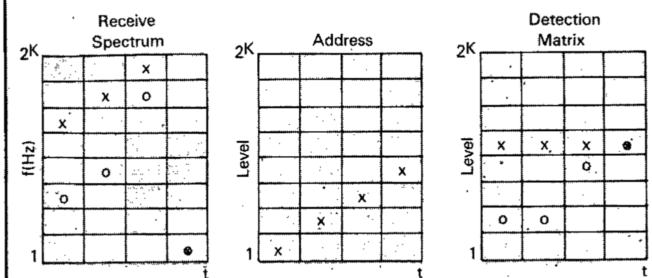


Fig. 9b. Matrices in Receive Portion. The matrices show reception of the frequencies in Fig. 9a (X) and reception of a set of tones (0) transmitted by one other user.

$$P_F = \exp(-\beta^2/2)$$

$$P_D = 1 - \exp(-\beta^2/2(1+\bar{\rho}))$$

where P_F denotes false alarm probability, P_D the probability of deletion (miss), β the normalized threshold set in the receiver and $\bar{\rho}$ the average signal to noise ratio. The above scheme, where the presence or absence of energy in each square of detection matrix is decided, together with majority logic decision is called "Hard-limiting Combining" [44]. Whereas the hard-limited receiver does not fully exploit the available statistics of the received signal, it can be shown to be not too inferior to an ideal likelihood receiver [45,33].

The results on spectrum efficiency η, defined earlier, show that η is maximum for W = 20 and decreases slightly as W is reduced to 5 MHz [46]. Thus, splitting the total available bandwidth of 20 MHz into smaller bandwidths will only lead to reduced efficiency. The effect of shadowing on the performance of hard-limited receiver was examined in [47]. The results show that the system capacity decreases to 130 users at $P_b < 10^{-3}$ for average SNR = 30 dB and log-normal shadowing standard deviation of 12 dB. Also, in cellular systems, additional degradation occurs due to interference from adjacent cells. It could be seen that the performance deteriorates rapidly without power control. A power control scheme was suggested and evaluated for base to mobile communication [48]. It was observed that with Rayleigh fading and an SNR of 25 dB, the number of users that could be accommodated in a single cell at

$P_b < 10^{-3}$ was about 115. This is a reduction of 55 users from the isolated cell case.

In the above analysis, it was assumed that the frequency separation between tones, namely $1/\tau$, was greater than the coherence bandwidth of the channel and hence, the assumption that all the tones fade independently. For typical $\tau = 11.6\ \mu$ sec., $1/\tau = 86$ KHz. However, the coherence bandwidth (defined with respect to correlation coefficient of 0.9) varies from < 0.04 MHz in urban areas to > 0.25 MHz, < 1 MHz in suburban areas [49]. Thus, it is possible that correlated fading could occur during deep fades and lead to error clustering [50,51].

Improved Address Assignment and Decoding

In FH-MFSK system considered so far, we assumed that the addresses are assigned randomly. Also, the probability of bit error P_b computed is the value obtained by averaging all the probability of bit errors resulting from an ensemble of all possible random address assignments. Naturally, this raises the question, "are there bound to be many links whose P_b will be very high, even though the average $P_b < 10^{-3}$?" We find the answer [52], "since only a fraction $1/\lambda$ of a set of positive numbers can be larger than λ times their average, at least 90 percent of all codes in the collection must have a P_b no greater than ten times average P_b, and 99 percent of all code must have a P_b no larger than 100 times average P_b." In fact, the result of this argument is verified by simulation studies [53]. The simulation is done assuming perfect channel, but multi-user interference is considered. It is noticed that maximum BERs (bit error rates) do not differ by more than a factor of 2 from the average BER. However, if the addresses are assigned in a "best possible way," each user could have a nearly identical performance. One possible scheme is discussed next.

In [41], the proposed addressing scheme assigns each user an address

$$\underline{a_m} = (\gamma_m, \gamma_m\beta, \gamma_m\beta, \ldots \gamma\, \beta^{L-1})$$

where $\gamma_m \in GF(Q)$

β is any primitive element of GF(Q).

Galois Field exists only for Q being prime or any integer power of a prime (Hence, Q can be 2^K) [35]. Coding of the user message m is done according to:

$$\underline{Y_m} = \underline{a_m} + \underline{x_m}$$

Observe that this equation is similar to a previous equation. It is easily shown that for synchronous communication, any two coded messages $\underline{Y_m}$ and $\underline{Y_e}$ ($m,e \in GF(Q)$, $m \neq e$) could coincide in one chip, at most. Then, it is clear that under ideal transmission, to create one spurious row in the decoded matrix at a user, at lease L users must have been involved. An error can occur in the decision process only if one or more spurious rows are created. A simple upper bound on probability of bit error indicates that this bound is slightly less than the average P_b bound obtained for random addressing. This agrees with our expectations.

Since the addressing scheme (above) possesses certain algebraic properties, it is possible to exploit these properties in the decoding of messages, thereby accommodating more number of users at a specified P_b, (say $< 10^{-3}$). Such an analysis carried out in [54] under ideal conditions shows that the scheme could accommodate nearly 450 users as compared to 216 with conventional decoding. Of course, the decoding scheme requires the knowledge of the addresses of all active users. Therefore, such information needs to be periodically transmitted to mobiles from base. Another difficulty is that the decoding procedure does not allow an easy performance evaluation under the conditions of noise and fading. Also, the complexity of decoding at the mobiles could be very high, making the algorithm useless under such a situation.

It is also possible to use space diversity of moderate complexity (2 or 3 branches) to improve the performance of FH-MFSK [4]. There are some recent results suggesting the possibility of space diversity with FM or PSK [55]. However, the number of diversity branches needed is greater than 20 or so and hence, the implementation becomes formidable. Another version of space diversity with PSK and time-division retransmission is suggested in [56].

Measures for Spectral Efficiency

In previous sections we used $\eta \left(= \frac{MR_b}{W}\right)$ as a figure of spectral efficiency. Apart from other drawbacks of this measure, there is one which has not been observed. With the use of efficient speech coding techniques, such as LPC, it is possible to reduce R_b to as low as 4 Kb/sec. Assume such coded speech, when passed through mobile radio channels, still possesses intelligibility. Then, with FH-systems it can be shown that M would increase considerably. However, because of the multiplication of M by R_b in the definition of η, the net increase (it could be a decrease too!) may not be much, and as such this is clearly misleading because LPC speech also carries effectively the same information over the same period. Hence, η is code dependent and cannot be applied to compare two systems employing different coding techniques. Some of the measures of spectral efficiency for land-mobile application and their usefulness are discussed in [57]. In general, a definition should include the number of mobiles served over what bandwidth and geographical area. Clearly η, as defined earlier, does not include the geometry factor. Finally, a measure which is useful for FM cellular systems expressed in Erlangs | $H_z\ m^2$. The reader is cautioned that assigning a minimum bandwidth per channel does not always lead to an overall spectrally efficient FM system. For example, allocation of 30 KHz per channel can be spectrally more efficient than an assignment of 15 KHz per channel [58]. Next, we discuss some of the aspects of voice and data transmission in FM-cellular systems, with specific references to AMPS.

Voice and Data Transmission

Voice Transmission

Speech can be transmitted by an analog modulation, such as FM, or by means of a digital radio, after coding the speech. While AM is conceptually possible, the rate of change and the depth of fades that can occur at UHF have not permitted satisfactory transmission quality to be obtained in this environment. We shall explain briefly the impairments expected on voice transmission and the measures possible to reduce these, when FM is employed. Specifically, we concentrate on AMPS (Advanced Mobile Phone System) [59,60]. Considering 850 MHz band, Fig. 10 shows a sample of Rayleigh envelope signal obtained at moving antenna measured along a short distance of travel. We observe that the Rayleigh fades occur approximately one-half wavelength apart. At carrier frequencies near 850 MHz, independent fades are about seven inches apart. As the mobile receiver moves through the radio interference pattern, it is therefore subjected to frequent fades. Figure 11 shows the probability distribution function of the received instantaneous signal power normalized to its mean-value. The no-diversity curve shows that the fades are such that 10 percent of the time the signal will be 10 dB below its local mean, 1 percent of the time 20 dB will be below the mean, and so forth. Also of interest are the quantities, the level crossing rate of the envelope below a specified level, as well as the duration of the fade below the specified level. These two quantities are

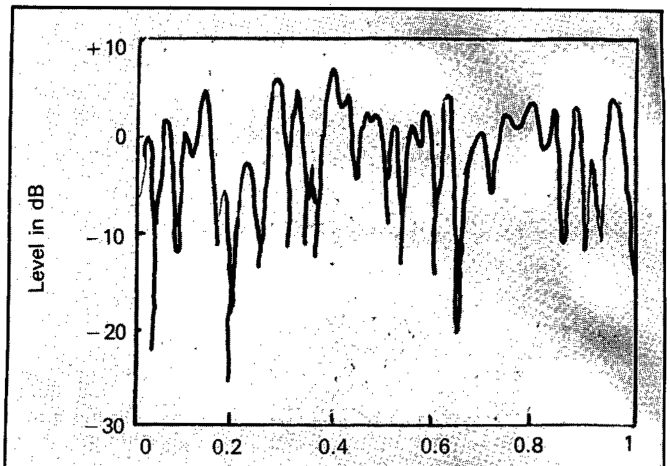


Fig. 10. Sample of Rayleigh Envelope (carrier at 850 MHz).

dependent on the vehicle speed. Apart from this Rayleigh fading, we have the "shadow fading" caused by terrain features.

In AMPS, discriminator detection is employed to demodulate voice signals. During the deep fades, the signal goes below noise level and the noise could "capture" FM receiver. These interruptions have a different subjective effect as a function of the speed. This is also called the "click noise." These clicks arrive in bursts and are time correlated with RF signal fades. At times during fades, the receiver may be captured by interference from a co-channel user. The result is a burst of interfering voice modulation which is unintelligible because of the short duration of fades. Sometimes, the frequency offset between the signal carrier and the co-channel carrier can be heard as a wobbling tone. Apart from these, we have the impulsive noise (due to ignition systems) which is predominant in urban areas. Since majority of the impairments come through fading, it is important to reduce the level, duration, and frequency of fades. This is accomplished by "diversity techniques" discussed earlier. Space diversity is attractive with FM systems. The effect of a two-branch equal gain combining diversity system is shown in Fig. 11. In AMPS, equal gain or selection diversity will be used at cell sites, whereas the mobiles, where the cost and complexity are important, will be provided with switched diversity. However, performance of switched diversity is not as good as equal gain combining [3]. In addition to the improvement through diversity, additional improvement with voice processing circuits are necessary and possible. For example, variations in talker volume can have significant effects on the subjective quality of the received signal. Low volume speakers induce low frequency deviations and hence, the received signal will be weaker. In contrast, speech from loud talkers is impaired through excessive clipping distortion in the transmitter. To overcome these problems, syllabic companders at the transmitter and the expanders at the receivers are employed.

Digital coding and transmission of speech has some attractive features, namely, inexpensive coder-decoder implementation, straight forward speech encryption (bit scrambling), and efficient signal regeneration. But in a mobile radio environment, the digital transmission too, faces the problem of fading. Without any effective diversity, errors tend to occur in bursts. Whereas an average bit error rate of 1 in 10^3 still gives good quality for ADM speech samples, an error rate of 1 in 10^2 is acceptable during short periods. However, since these errors do not occur independently but rather in bursts, they have annoying effects on the listener. There has not been much discussion on this subject, except for a few papers. In [61], a differential code with explicit transmission of step size over an error protected channel, was analyzed for its performance by simulation studies. Effect of redundant time diversity coding and bit scrambling was also investigated.

Data Transmission

In the AMPS system discussed above, direct binary frequency shift keying of the carrier with discriminator detection was employed. The main source of impairment is once again the error clustering during fade. Use of error correcting codes (40, 28 BCH code) along with message repetition and majority voting at the receiver are considered as measures against burst errors.

Recently, there has been interest in finding efficient modulation techniques for data transmission in telephone, as well as, satellite networks [62,63]. In telephone lines, the bandwidth is at a premium and hence, spectrally efficient techniques to send data at higher rates are important. Some of these schemes, which possess narrow spectrum, also have constant envelope. The constant envelope property is important in satellite channels where the nonlinear operations used (hard-limited or class C power amplifiers) to create adjacent channel interference, if the envelope is not constantly maintained. These features are attractive for data transmission in cellular mobile radio [64]. Two modulation schemes known as MSK (minimum shift-keying), which is also called Fast FSK, and TFM (Tamed Frequency Modulation) can be considered [63,65]. MSK can be thought of as a special case of offset QPSK. In normal QPSK, the incoming data stream is split into "odd" and "even" streams and are used to modulate the quadrature and in-phase carriers, respectively, (see Fig. 12). Because of the orthogonality of the two carriers, it is possible to recover the "odd" and "even"

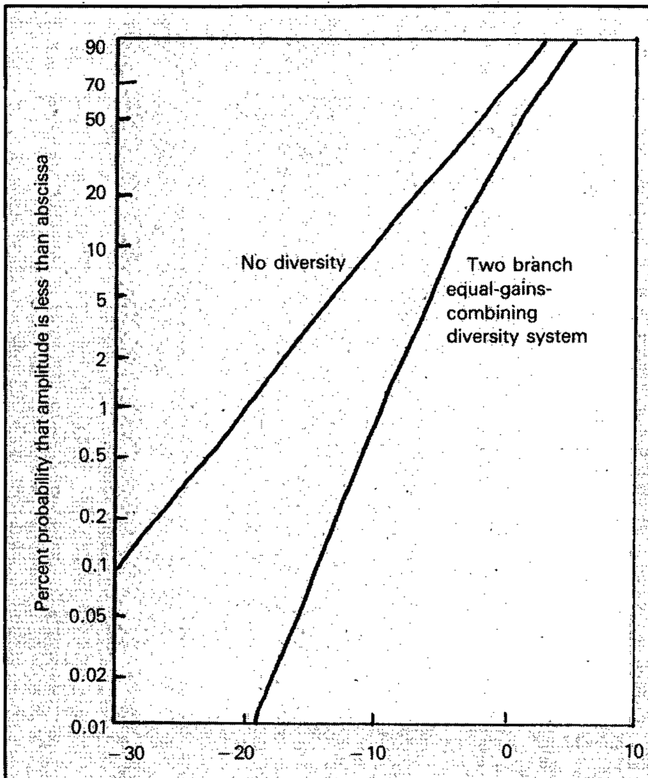


Fig. 11. Effect of diversity.

streams exactly at the receiver, when there is no channel impairment. Whereas in QPSK, the bit transitions occur at the same time, in OQPSK, their occurrences differ by $\pi/2$ radians. Because of this, the phase changes in OQPSK waveform at bit transitions can only be $\pm\pi/2$, which is in contrast to $\pm\pi$ and $\pm\pi/2$ changes possible in QPSK. This helps in out of band radiations to be reduced in OQPSK. With sinusoidal pulse weighting in offset DPSK the resulting waveform S(t) can be written as (Fig. 12):

$$S(t) = a_I\ (t)\ \cos\left(\frac{\pi t}{2T}\right)\cos(2\pi f_c t) + a_Q(t)\sin\left(\frac{\pi t}{2T}\right)\sin 2\pi f_c t$$

Using standard trigonometric formulae this can be rewritten as:

$$S(t) = \cos\left[2\pi f_c t + b_k(t)\frac{\pi t}{2T} + \phi_k\right]$$

Where $b_k(t) = -a_I(t)\, a_Q(t)$ and ϕ_k is 0 or π corresponding to $a_I=1$ or -1.

From the above equation we observe the following properties of MSK:

1) It has constant envelope.
2) There is phase continuity in the RF carrier at the bit transitions.
3) The signal is an FSK signal, with continuous phase and with the frequency spacing $\Delta = (f_c + 1/4T) - (f_c - 1/4T) = 1/2T$. This is the minimum frequency spacing which allows the two FSK signals to be coherently orthogonal, hence the name minimum shift keying.

Whereas the phase is continuous in MSK, the derivative of the phase is still discontinuous (implying phase is only piecewise continuous). If the phase is made still smoother, a much narrower spectrum can be achieved. One method of modulation achieving this is called the TFM [64]. Some comparison between MSK and TFM is as follows:

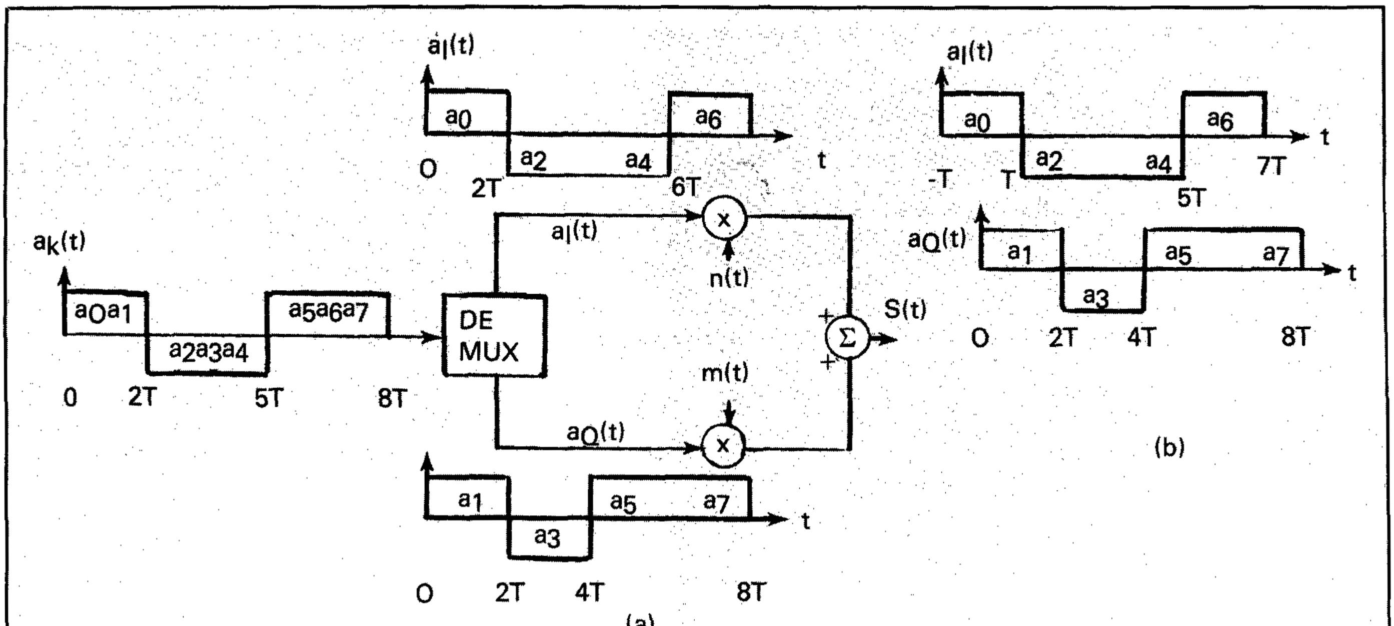
1) Both are spectrally efficient, though the sharper roll-off of the spectrum of TFM can be advantageous in reducing adjacent channel interference.
2) Both are easy to generate.
3) In principle, coherent, differential, and discriminator detection can be employed for MSK and only the first two types for TFM. It can be shown that error rate performance of coherently decoded MSK is equivalent to that of PSK (Quartennary PSK) whereas, coherent detection of TFM has a loss of 1 dB. Differential detection of MSK is simple to implement but is slightly less efficient than coherent detection. A coherently detected TFM for digital speech, which performs nearly as good as conventional narrow band FM is given in [64].

In general, it is not easy to construct a simple carrier recovery circuit which enables one to regenerate the reference carrier precisely and stably in the fast Rayleigh fading channels. The performances of the differential detection receivers in mobile radio channels for MSK and TFM can be found in [66] and [67].

Clearly, some of the spectrally efficient techniques could soon find a place in the digital data transmission over mobile radio.

Conclusion

This tutorial paper looks at some of the theoretical and design issues involved in mobile radio communication. While the review is not exhaustive, many references are given to supplement the material presented.



$$n(t) = \frac{1}{\sqrt{2}}\cos(2\pi f_c t + \pi/4)$$

$$m(t) = \frac{1}{\sqrt{2}}\sin(2\pi f_c t + \pi/4)$$

Fig. 12. a) QPSK modulator. b) Staggering of data streams in OQPSK.

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