THE CHOICE OF A DIGITAL MODULATION SCHEME IN A MOBILE RADIO SYSTEM

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ABSTRACT - The modulation scheme that should be adopted in a mobile radio communication system must primarily satisfy the objective of achieving high spectral efficiency and narrow power spectrum. The paper describes the emerging modulation technologies in the family of linear modulation and constant envelope techniques. The multilevel modulation, spectral efficiency, power spectrum and inter symbol interference are discussed. The effect of coding on transmission rate and improvement in SNR requirement is considered.

I. INTRODUCTION

A modulation scheme used for mobile environment should utilise the transmitted power and RF channel bandwidth as efficiently as possible. This is because the mobile radio channel is both power and band limited. To conserve power, efficient source encoding schemes are generally used but this is at the cost of bandwidth. Whereas to save the spectrum in band limited systems, spectrally efficient modulation techniques are used. The objective of spectrally efficient modulation is to maximize the bandwidth efficiency. It is also desirable to achieve the bandwidth efficiency at a prescribed BER with minimum transmitted power.

Coming to the cost aspect - To satisfy the requirement of power economy, class C amplifiers are preferred. Hence, a trade off between power spectrum efficiency and spectral efficiency has to be made keeping in view the system complexity. Care has to be taken to ensure that the hardware complexity and the cost are properly weighed.

II. DIGITAL MODULATION TECHNIQUES

Among the many digital modulation techniques in use, some are responsive primarily to the goal of spectral efficiency, while others focus on the objective of achieving a narrow power spectrum. The large variation in signal amplitude due to Rayleigh fading encountered, render the digital amplitude modulation schemes almost inoperative. There are basically two broad modulation strategies emerging which emphasize the use of PSK or MSK derived modulation schemes.

A. Linear Modulation Techniques

The family of linear -modulation techniques require a high degree of linearity in modulating the carrier by baseband signal and RF power amplification before transmission. Linear modulation is more spectral efficient, but requires a linear power amplifier so as to avoid the signal amplitude variations which may result in intermodulation products.The most important linear modulation methods are QPSK, OK-QPSK, $\Pi/4$ shift QPSK and higher -level PSK.

Quaternary Phase Shift Keying (QPSK) : A generalised model of QPSK modulator is shown in Figure 1(a). QPSK is characterised by two parts of the baseband data signal the inphase signal I(t) and the quadrature signal Q(t). For this reason the data rate of individual signals, I(t) and Q(t), is half that of the base band signal. This also cuts the bandwidth requirement of QPSK to 1/2 as compared to BPSK. The modulated signal has 180 and ±90 degree phase shifts. The signal transitions are abrupt and unequal and this causes large spectrum dispersion. QPSK also needs more power and higher CNR (approx. 3 dB) than BPSK, to obtain the same performance for same probability of error.

Offset Keyed QPSK (OK-QPSK) : The difference between QPSK and OK-QPSK is in the alignment of the in phase signal I(t) and the quadrature signal Q(t). OK-QPSK is obtained by introducing a shift or offset equal to one bit delay (Tb) in the quadrature signal Q (t). See Figure 1(b). This ensures that the I(t) and Q(t) signals have signal transitions at the time instants separated by Ts/2. The modulated signal transitions are ±90 degree maximum. It has no 180 degree phase shift and this results in reduction of out of band radiations. However, the abrupt phase transitions still remain.

$\Pi/4$ *Phase Shift QPSK* : $\Pi/4$ -QPSK is a compromise between QPSK and OK-QPSK. It can be regarded as a modification to QPSK and has carrier phase transitions which are restricted to ±45 degree and ±135 degree. A block diagram of $\Pi/4$ shift QPSK modulator is shown in figure 1(c). Like OK-QPSK the carrier phase does not undergo instantaneous 180 degree phase transition. Thus, the main advantage is that of the reduced envelope fluctuation as compared to that of QPSK. The BER performance of the $\Pi/4$ shift QPSK is controlled by CCI rather than fading. The fact which is very important for cellular mobile radio systems which work on frequency reuse concept and where CCI is the major source of interference. [5].

B. Continous Phase Modulation Techniques

Continuous-phase modulation schemes avoids the linearity requirements which reduces the cost of amplification. Modulation techniques derived from the CPM family have quite narrow power spectra. On the other hand, the spectral efficiency is somewhat lower. Among the important constant envelope or continuous phase modulation schemes being explored currently are MSK and GMSK.

Minimum Shift Keying (MSK) : MSK can be regarded either as a special case of OK-QPSK or as a form of FSK modulation. The baseband signal is filtered sinusoidaly to produce a graceful transition from one binary state to another. MSK is a binary modulation with symbol interval Tb and frequency deviation = ±1/4Tb. And there is phase

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continuity of the modulated RF carrier at the bit transitions. RF phase varies linearly exactly ±90 degree with respect to the carrier over one bit period Tb.

Gaussian Minimum Shift Keying (GMSK) : The use of a pre-modulation low- pass filter with a Gaussian characteristics with the MSK approach · achieves the requirement of uniform envelope, in addition to spectral containment. This modulation scheme is known as GMSK (Gaussian MSK). The Gaussian filter is used to suppress out of band noise and adjacent channel interference. GMSK provides high spectrum efficiency and a constant amplitude signal that allows class C power amplifiers to be used minimising power consumption, weight and cost. [2].

Tamed Frequency Modulation (TFM) : In MSK the phase continuity is achieved, but the derivative of the phase is still discontinuous. If the phase change is made still smoother, a much narrower spectrum can be achieved. A scheme involving pre-filtering combined with an algorithm for selecting the carrier phase shift, according to the original data values, has been developed. This scheme, known as Tamed Frequency Modulation (TFM), has spectral containment characteristics similar to GMSK. [1].

III. SPECTRAL EFFICIENCY

Spectral efficiency is defined as the number of bits per second per hertz (b/s/Hz). Spectral efficiency influences the spectrum occupancy in a mobile radio system. Theoretically, an increase in the number of modulation levels results into higher spectral efficiency. But the precision required at the demodulator to detect the phase and frequency changes also increases exponentially. Which results into higher S/N requirement to achieve same BER performance. Table I shows the comparison of spectral efficiency and the required S/N (for BER of 1 in 10^6) for PSK and MSK modulation systems.

The QPSK-type linear modulation schemes have recently drawn more attention, since they offer higher spectral efficiency and are considerably simpler to be implemented. The north American (ADC) and Japanese (JDC) digital cellular systems currently under development employ Π/4 phase shift QPSK.

TABLE I - COMPARISON OF MODULATION SYSTEMS

MODULATION	SPECTRAL EFFICIENCY	REQUIRED S/N
BPSK	**1 b/s/Hz**	**11.1 dB**
QPSK	**2 b/s/Hz**	**14.0 dB**
PSK (16 level)	**4 b/s/Hz**	**26.0 dB**
MSK (2 level)	**1 b/s/Hz**	**10.6 dB**
MSK (4 level)	**2 b/s/Hz**	**13.8 dB**

Table II summarises various modulation schemes adopted in second generation cellular and cordless telephone systems. It is observed that though linear modulation schemes offer better spectral efficiency, GMSK is also considered as a promising modulation scheme. The European GSM (Group Speciale Mobile) system is based on GMSK with a bit rate of 271 kbps and Bb.T = 0.3. The DECT (Digital European Cordless Telephone) system uses GMSK with Bb.T = 0.5 at a data rate of 1.152 Mb/sec..

The choice between linear modulation and constant envelope modulation technique is influenced by the fact that how much maximum spectral efficiency must be stressed in comparison with cost and size, and also the requirement of adjacent channel selectivity.

TABLE II - SPECTRAL EFFICIENCY OF DIGITAL CELLULAR and CORDLESS TELEPHONE SYSTEMS

SYSTEM	MODULATION TECHNIQUE	CHANNEL B.W. KHz	DATA RATE Kbps	SPECTRAL EFFICIENCY b/s/Hz
JDC	Π/4 QPSK	25	42.0	1.68
ADC	Π/4 QPSK	30	48.6	1.62
GSM	GMSK (BbT=0.3)	200	270.8	1.35
CT-2	GMSK	100	72.0	0.72
DECT	GMSK(BbT=0.5)	1728	1572.0	0.67

Bb is the pre-modulation filter bandwidth.

IV. INTERSYMBOL INTERFERENCE

One of the effects produced by mobile environment is the distortion of the signal due to delay spread, which results in intersymbol interference. It is known that if the effects of delay spread are ignored or equalized, the spectral efficiency improves for higher level modulation. And this is realised at the cost of high SNR. Theoretically, the impact of delay spread can be reduced by adopting higher level modulation techniques. For example, a 4-level modulation signal transmitted at the data rate of 200 kbps would have symbol duration of about 10us as against 20 us in 16-level modulation. However, under the influence of delay spread, the simulations indicate that no significant performance improvement can be achieved as the level of modulation exceeds 4, even if SNR approaches infinity. It is indicated that BER performance depends strongly on the rms value of delay spread. Thus a 4 level modulation scheme seems to be reasonable when delay spread is significant. [4].

V. POWER SPECTRUM EFFICIENCY

The energy of a modulated carrier is distributed in the main lobe and side lobes. The power spectrum is a determinent of adjacent channel interference.

A power efficient digital communication system will have to be non linearily amplified for cost effective utilization of power. When a band limited linearly modulated carrier undergoes non linear amplification, the filtered side lobes re-appear. This causes severe adjacent channel and co-channel interference. The BER performance is also degraded. Hence, such systems may not efficiently utilize the available frequency spectrum. Power efficiency gained is lost as a result of non linear amplification.

The power spectrum density for QPSK is given by eq. (1)

$$W(f-fc) = \frac{A}{2} \cdot Ts \cdot \left[\frac{\mathrm{Sin}\{\pi \, Ts \, (f-fc)\}}{\{\pi \, Ts \, (f-fc)\}} \right]^2 \qquad (1)$$

Where fc is the unmodulated carrier frequency, A is a constant proportional to the total transmitted power and Ts is the symbol period. The equation (1) is valid for BPSK, QPSK and multilevel PSK as long as the symbols are mutually independent.

Constant phase modulation techniques can be non linearly amplified without significant spectral regeneration. The power spectrum density for MSK is given by equation (2).

$$W(f-fc)=\frac{A^2 . Ts}{4\pi^2}\left[\frac{\cos(\pi f \; Ts)}{\{(f \; Ts - fc \; Ts)^2 - 1/4\}}\right]^2 \qquad (2)$$

Figure 2 shows the power spectrum distribution of QPSK and MSK. The difference in time alignment of the bit streams for QPSK and OK-QPSK does not change the power spectral density distribution. The difference in power efficiency using QPSK or Π/4 shift QPSK is very small. We see that QPSK has a side lobe level about 12 dB and MSK has about 24dB down from the carrier. The power spectrum of MSK signal concentrates more around the main lobe and decreases more quickly in the other side lobe areas i.e. the power spectrum of MSK signal decreases with f(-4) while that of QPSK decreases with f(-2). MSK is more spectrum efficient than QPSK but it has a wider main lobe.

Figure 3 shows the computed results of power spectra of GMSK for various values of BbT. [6]. It is observed that the spectrum occupancy can be controlled by the normalised 3dB BbT of the Gaussian premodulation filter.

If BbT is infinite this gives a phase change of 90 degree in each interval, which is MSK modulation. The power spectral density of GMSK with BbT = 0.2 is nearly equal to that of TFM. The value of BbT can be selected considering overall spectrum efficiency requirements. The spectral spread is nearly the same till 1/T but beyond that both QPSK and GMSK differ significantly. Among all these schemes the complexity of QPSK is considered to be high.

VI. OUT OF BAND POWER

In a channel without any bandwidth restriction, the QPSK modulated carrier has a uniform envelope but a wide spread of sideband energy. To contain this, post filtering (bandwidth equal to 1.1RL) can be adopted. The filtering is acceptable to receivers, but the effect of filtering has been to introduce carrier amplitude variations. If the signal is transmitted through a nonlinear power amplifier in the transmitter, then the amplitude variations result in the regrowth of the side lobes, which effectively expand the bandwidth again.

Figure 4 shows the computed results of fractional power outside the desired normalised channel bandwidth for various values of BbT. [6]. It is seen that for a non filterd MSK signal 99% of the power is contained within a channel of bandwidth equal to 1.2RL. Where as for GMSK (BbT=0.5) it is contained within a channel of bandwidth equal to 1.04RL and for GMSK (with BbT=0.2) in a channel of bandwidth equal to 0.79RL.

The out-of-band emission performance of QPSK and Π/4 shift QPSK is almost the same when a reasonably linear amplifier is used. [8]. For QPSK 99% of the power is contained in a channel bandwidth equal to 8RL as compared to 1.2RL for non filterd MSK signal. Thus less post modulation filtering will be required for MSK than for QPSK to reduce the out of band power to a given value. The first null of the MSK signal occurs at 0.75, while that of QPSK occurs at 0.5 of the bit rate. A narrow post modulation filter removes more energy from the first lobe of MSK than that of PSK and introduces more intersymbol interference. The literature shows different values for an optimum channel bandwidth from the implementation point. Ishizuka and Hirade [7] claim an optimum for Bc=0.59RL. In a realistic radio channel using class C power amplifier a Bc = 0.75RL is a realistic optimum assumption. Minimum spectral dispersion and a uniform envelope for the modulated carrier are, therefore, important targets to aim for. QPSK appears to be non ideal on both counts.

VII. EFFECT OF CODING

The carrier modulation and coding though are logically independent process but are strongly interrelated. The improvement in either of them is towards achievement of a common goal of higher spectral efficiency. Higher level modulation offers higher spectral efficiency but higher SNR is required to achieve a given BER objective which is difficult to achieve in a mobile environment. The required S/N can be reduced by using low bit rate voice coding and efficient error correction techniques prior to modulation.

The selection of a coding technique is mainly driven by achieving the desired voice quality by adding minimum overhead while protecting the information bits to fight the channel noise. This strategy is assisted by treating those bits within a message which decide the speech quality, separately from those which are less critical.

LPC-RPE speech coder used in GSM cellular system operates at 13 kbps data rate. The most sensitive bits are protected by a CRC code with rate = 1/2 convolutional code with constraint length 5. The overall coded bit rate per speech signal is 22.8 kbps. To combat the channel noise, 30% overhead (10.1 kbps) as guard time, synchronization, etc and 0.95 kbps as SACCH is added before transmission. Thus the gross bit rate is 33.85 kbps per channel and 270.8 kbps for 8 channels. The spectral efficiency of GSM system employing GMSK modulation (BT=0.3) operating with a 200 KHz channel spacing is 1.35 b/s/Hz.

The speech coding technique adopted for ADC system is VSELP operating at 7.95 kbps. The channel coding used is a convolutional code with constraint length 6. The overall coded bit rate is 13 kbps only. With 16% overhead and 0.6 kbps SACCH, the overall bit rate is 16.2 kbps per channel and 48.6 kbps for 3 channels. The spectral efficiency (1.6 b/s/Hz) is better than that of GSM system. The ADC system uses Π/4-QPSK modulation with 30 KHz channel spacing.

Traditional LPC -type coders are capable of handling very low bit rates (1.2 - 4.8 kbps), but tend to be extremely vulnerable to errors. RELP coder operating at 8 - 16 kbps and Subband coders operating at 16 kbps have also proved to be fairly robust.

VIII. CONCLUSION

Both presented digital modulation schemes have been used extensively in mobile communication systems. The selection of one over the other depends on the priorities set in the system requirements. If most efficient bandwidth utilisation and moderate hardware complexity is the key note - QPSK (Π/4 QPSK) will be a better choice. Whereas continuous phase modulation schemes offer constant envelope, narrow power spectra, good error rate performance, etc. Therefore when out of band signal power, tolerance against filter parameter and non-linear power amplifiers are important features, compromise in channel separation is permissible and higher circuit complexity is of less consideration- GMSK is the solution. Spectral efficiency can be further improved by using suitable coding technique. Digital modulation scheme combined with robust coder which can inherently withstand higher bit error rates needing less channel coding will be the ultimate choice for a spectrum efficient mobile system.

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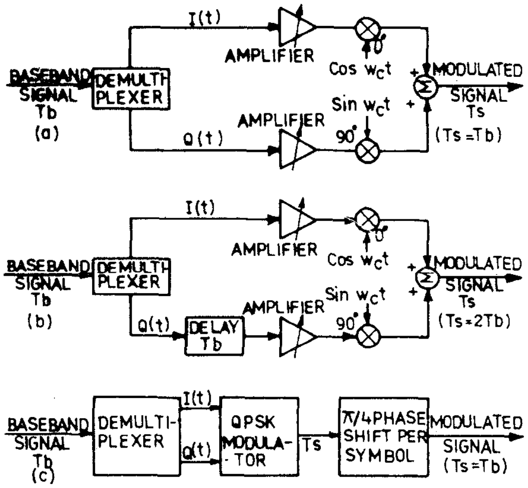

Fig. 1: Generalised Model of (a) QPSK; (b) OK-QPSK; (c) π/4-QPSK

Tb: Baseband data Rate, Ts: Symbol Rate

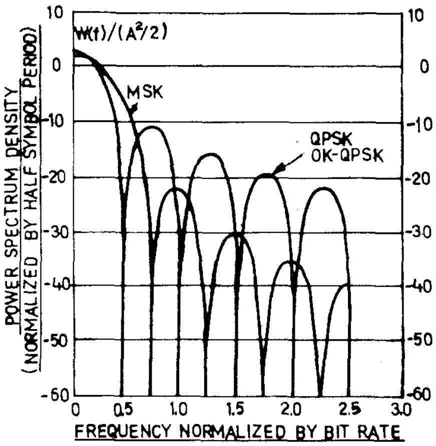

Fig. 2: Power spectra of QPSK and MSK

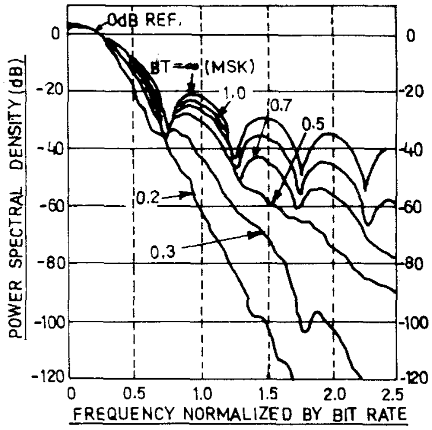

Fig. 3: Power spectra of GMSK signals

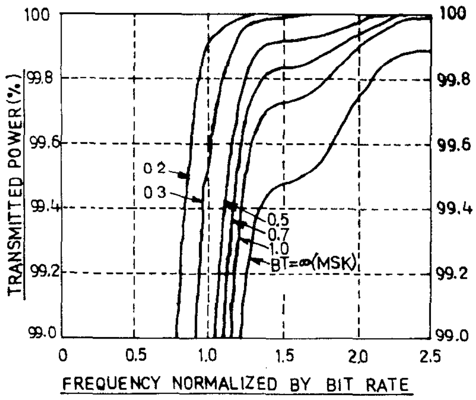

Fig. 4: Fractional Power Ratio - GMSK signals