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A Comparative Performance Analysis of Digital Modulation Schemes used in Mobile Radio Systems

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Abstract: *This paper best describes a MATLAB based approach for comparing performances of digital modulation schemes used in mobile radio communication channels which are affected by the well known pitfall of the wireless communication channels, fading. Specifically, this paper introduces the basic concepts for digital modulation schemes such as M-PSK (M-ary Phase Shift Keying) and M-QAM (M-ary Quadrature Amplitude Modulation) and simulates propagation process in AWGN or Rayleigh fading channels of Phase Shift Keying and Quadrature Amplitude Modulation and a wireless link numerical example taking into consideration parameters like channel bandwidth, bit error rate, bit rate, energy of symbol or probability of error. Furthermore, based on the results it can be observed which one of the modulation scheme has the most increased capacity and which one has the best performance according to the values of BER and SNR..*

Keywords: *BER; SNR; M-Ary PSK; M-Ary QAM; AWGN, Fading.*

1. Introduction

In the past few years with the evolution of processing technologies of information, mobile communication networks were developed to gain and offer the advantages of mobility to users. [1] Mobile communication systems must offer robust and flexible communications anytime, anywhere and to anyone. Robust communications imply bit error probabilities and few packets and on the other hand flexible communications imply adaptation of binary data rates, of delays and error probabilities assured by the time the offered service is executed (real time or not : voice, data, video streaming etc.). Increase of binary data rates in a communication system can be achieved by increasing the symbol frequency of transmission (which leads to an increase of the required frequency bandwidth) or by increasing the quantity of information which is transmitted over a symbol. Therefore, increasing the data rate of a transmission with limited frequency bandwidth, with keeping the error probability, is possible only by assuring a high level of the signal to noise ratio (SNR) at the reception side, where in practical situations it is hard to be achieved.

2. Digital Modulations

Most of the communication systems depend on one of three parameter categories: bandwidth efficiency, power efficiency and cost efficiency. [2] Bandwidth efficiency best describes the ability of a modulation scheme to fit data within a limited frequency bandwidth. Power efficiency describes the ability of the communication system to send information at the lowest practical power level without affecting the channels distribution. The parameter to be optimized depends on the system that needs to be designed. For example in digital terrestrial radio communications the highest priority is to obtain a good bandwidth efficiency with low bit error rate and parameters like power available, power efficiency and receiver cost are parameters that don't need to be especially concerned about. On the other hand, designers of mobile phones put their highest priority on power efficiency because the terminals need to run on battery. Moreover, migration to digital modulations provide more information about capacity, compatibility with digital data services, higher data security, better quality communications, and quicker system availability.

Therefore, digital mobile systems must meet the following general requests:

- Efficient usage of frequency bandwidth;
- Good performances concerning the bit-error-rate (BER);
- Efficient usage of the battery of the mobile terminal;
- Applicability in cellular systems;
- Acceptable complexity of system design.

A measure of modulation efficiency is the distance between the channels, which has to be as low as possible. Assuming that the radiofrequency spectrum aliasing of the adjacent channels is forbidden, the distance between the channels is given by:

$$f_s = B + 2\Delta f + \Delta D \quad (1)$$

where B is the occupied bandwidth of the radio frequency signal, Δf represents the central frequency deviation of the carrier and ΔD represents the frequency deviation of the Doppler effect. The frequency bandwidth of the transmission is given by $B=R_d/m$, where R_d represents the data rate and m the usage efficiency of the spectrum. Therefore, equation (1) can be written as:

$$f_s = \frac{R_d}{m} + 2\Delta f + \Delta D \quad (2)$$

For decreasing the distance between the channels in mobile telecommunication systems the following possibilities need to be taken into consideration:

- Decrease the data rate after voice coding;
- Decrease the occupied frequency bandwidth by using an efficient digital modulation and increase the value of m;
- Decrease the frequency deviation of the carrier.

Concerning the frequency deviation due to Doppler effect, it can not be taken actions on because it is given by the velocity of the mobile terminal. The central frequency deviation of the carrier is determined by stability of the local oscillator. [3] Taking into consideration the requests of simplicity, miniaturization and low power consumption, it becomes quite hard to build an oscillator with a frequency stability less than 10^{-6}/year. Furthermore, assuming a frequency stability of two adjacent channels limited at the value of $2x10^{-6}$/year, it is obtained a value for $\Delta f \leq 2$ kHz for 900 MHz channel.

In cellular radio applications where multipath propagation is taken into account, the value of m is between 1bps/Hz and 2bps/Hz. Choosing a value for m greater than 2 determines a degradation for the value of BER. For a channel of 25 MHz (GSM situations), the maximum data rate is situated between 22kbps and 45 kbps, for 1bps<m<2bps. Choosing the type of modulation and transmission parameters, in GSM system, leads to a data rate of 34kbps/25Hz.

2.1. PSK Modulation (Phase Shift Keying)

For PSK binary modulation (BPSK), signals are given by:

$S_0(t) = A \times \cos(\omega t)$ for binary "0"

and

$S_1(t) = A \times \cos(\omega t + \pi)$ for binary „1" (3)

[4] For M-PSK modulation type, there are needed M different phases, each n bit ($M=2^n$) of the binary stream is coded as a unique signal which is transmitted as:

$A\sin(\omega t + \theta j)$, where j=1…M (4)

2.2. QPSK Modulation (Quadrature Phase Shift Keying)

QPSK modulation is given by the existence of 4 signals, which are phase-shifted with 90□. The input bit stream $\{d_k\}$, $d_k = 0,1,2,\ldots$ is received at the modulators input at speed of 1/T bits/s, being separated into two strings of data $d_I(t)$ and $d_Q(t)$, which contain even and odd bits: $d_I(t)$=d0,d2,d4… and $d_Q(t)$ = d1,d3,d5…

For obtaining a QPSK modulated signal, s(t), are modulated in amplitude the in-phase and quadrature data streams, with a cosine and sinus carrier:

$$s(t) = \frac{1}{\sqrt{2}} dI(t)\cos\left(2\pi ft + \frac{\pi}{4}\right) + \frac{1}{\sqrt{2}} dQ(t)\cos\left(2\pi ft + \frac{\pi}{4}\right) \quad (5)$$

Knowing properties of trigonometric functions, equation (5) can be written as:

$$s(t) = A\cos(2\pi ft + \frac{\pi}{4} + \theta(t)) \quad (6)$$

The data stream $d_I(t)$ modulates the cosine function with an amplitude of ± 1, being equivalent with a phase deviation of cosine function with 0 or π; thus it is obtained a BPSK type waveform. Similarly, the data stream $d_Q(t)$ modulates the sinus function, obtaining an orthogonal BPSK waveform over cosine function. By adding these two orthogonal signals, a QPSK waveform is obtained. The values of θ(t) = 0, -π/2, π/2, π represent the four possible combinations of $d_I(t)$ and $d_Q(t)$.

[5] Each one of the four phases of the carrier represents 2 bits of data, resulting 2bits/symbol. Because the symbols velocity of QPSK represent ½ of bits velocity, it can be transmitted twice as much of data streams comparing with BPSK (same bandwidth). This situation is possible because the I and Q signals (imaginary and real), being orthogonal, it can be transmitted without any interference between them.

2.3. OQPSK Modulation (Offset Quadrature Phase Shift Keying)

If two bit strings I and Q are phase-shifted with t=1/2 x bit duration, the amplitude variations are minimized, phase of the signal is never shifted with 180^0. OQPSK is obtained from QPSK by shifting d_Q with t by the string d_I. Thus, the possible phase transitions are 0^0 and 90^0 and appear twice as often, but with half of the intensity of QPSK. Although there are amplitude variations between the transmitter and the receiver, in OQPSK these have a lower magnitude than in QPSK.

2.4. MSK Modulation (Minimum Shift Keying)

MSK modulation is obtained from OQPSK by replacing the rectangular impulse with a sinusoidal one (half period). MSK signal is defined by:

$$S(t) = d(t)\cos\left(\frac{\pi t}{2T}\right)\cos 2\pi ft + d(t)\sin\left(\frac{\pi t}{2T}\right) \quad (7)$$

In MSK modulation the phase shifts are linear and limited at $\pm\pi/2$ over period of a bit, T. Comparing with QPSK, MSK has the advantage that because of the linear phase shift, the power spectral density has the side lobes much smaller, which leads to a more efficient way of controlling the interference between the adjacent channels (the central lobe is much wider than in QPSK).

3. The Effects of Fading

Reception of digital modulated signals of a radio channel with fading is strongly affected and the error rate at the reception side increases in a considerable way. For a cvasi-stationery fading, which means negligible variations of the amplitude of the received signal over a period ofL symbols, the synchronization circuits can assure a carrier with a reference phase at the receptions side, thus a coherent modulation can be chosen.

3.1. AWGN (Adittive White Gaussian Noise)

AWGN is usually a universal model for the transmission channel. [6] All the channel does is adding the white noise that passes through it. This implies a flat frequency-amplitude response of the channel (infinite bandwidth) and a linear frequency-phase response (the signal passes without any distortions of amplitude or phase). The received signal is given by:

$$r(t) = s(t) + n(t) \quad (8)$$

where n(t) is the white noise. It has a constant power spectral density at any frequency.

$$N(f) = N_0/2 \text{ for } -\infty < f < \infty \tag{9}$$

Thus a white noise has an infinite power. According to Wiener-Khinchine the autocorrelation function of the white noise is given by:

$$R(\tau) \triangleq E\{n(t)n(t-\tau)\} = \int_{-\infty}^{\infty} N(f) e^{j2\pi f\tau} df = N_0/2 \times \delta(t) \tag{10}$$

where δ(t) is the Dirac function. The above equation shows that the samples of the white noise are uncorrelated no matter the time the samples are taken.

The amplitude of n(t) follows a gaussian distribution of the density probability function:

$$p(\eta) = \frac{1}{\sqrt{2\pi\sigma^2}} \times e^{-\frac{\eta^2}{2\sigma^2}} \tag{11}$$

where η represents the values of the random process n(t) and σ^2 represents the variation of the random process. Furthermore, it is interesting the fact that $\sigma^2=\infty$ for a white noise because σ^2 represents the strength of the noise.

4. Results and Discussions

The first part of the simulation consists in observing how the quality of the signal varies at the receivers side when it is affected by fading and the value of SNR is low. The principle used in this part of the simulation is to transmit an original signal, modulate it, pass it through AWGN or Rayleigh fading and plot it at the receivers side.

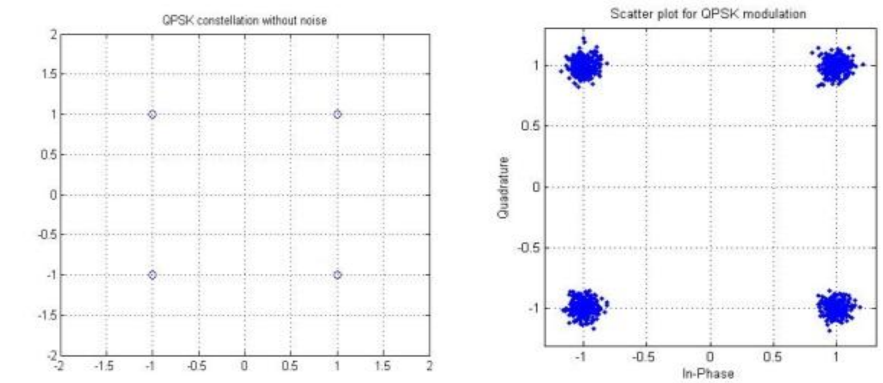

Fig1. *Transmitted QPSK signal and received QPSK constellation for SNR = 24 dB*

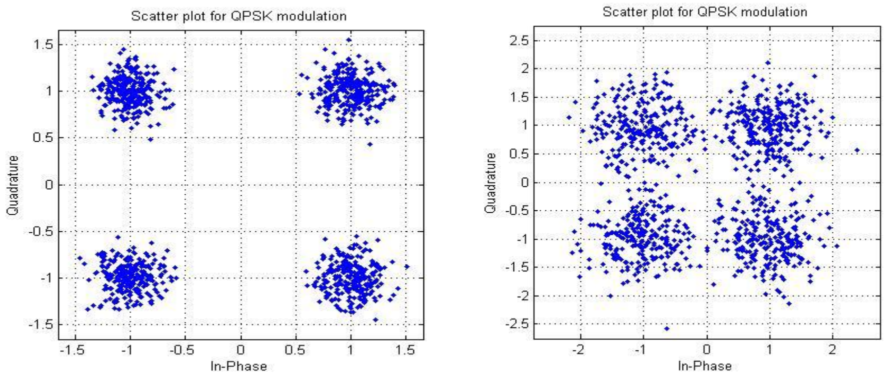

Fig2. *Received QPSK constellation for SNR = 16 and 8 dB*

From the figures above it can be observed that the quality of the signal decreases when the value of SNR (and Eb/No) also decreases. In practical situations solutions must be found to check whether the signal has reached its limitation point and must be attenuated or needs to be amplified. [7] Either way with a low value of SNR and BER the intelligibility of the carrier is strongly affected, especially in mobile communications where fading is much deeper than in other types of communications. From the figures below when the value of SNR drops below 6dB it can be observed that the scatter plot of the QPSK modulation can not even be distinguished.

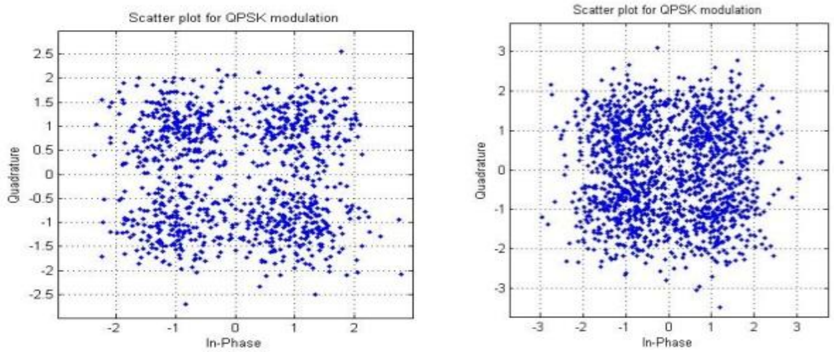

Fig3. *Received QPSK constellation for SNR = 6 and 4 dB*

In the second part of the simulation, Bit Error Rate (BER) and Symbol Error Rate (SER) were computed by: generating random bits to be transmitted, using gray code map to symbols of different modulations, mapping to closest symbol, taking decisions accordingly and adding all the errors at the receivers side. The results show that an acceptable value of BER/SER (10^{-6}) is obtained when the values of Eb/No (Energy Bit to Noise ratio) or Es/No (Energy symbol to Noise ratio) are greater than 10 dB.

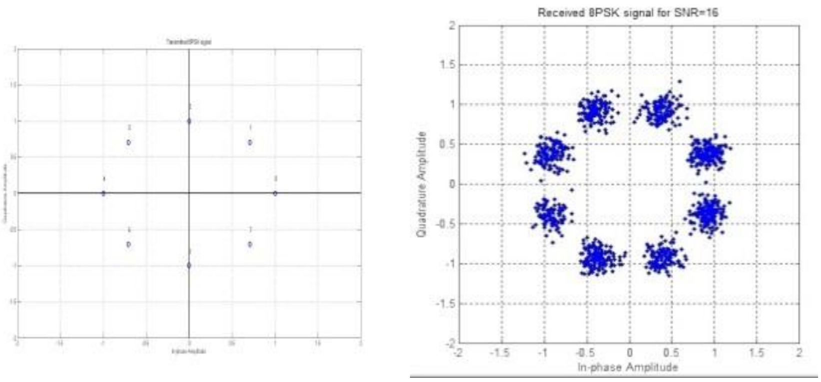

Fig4. *Transmitted 8PSK signal and received 8PSK constellation for SNR = 16 dB*

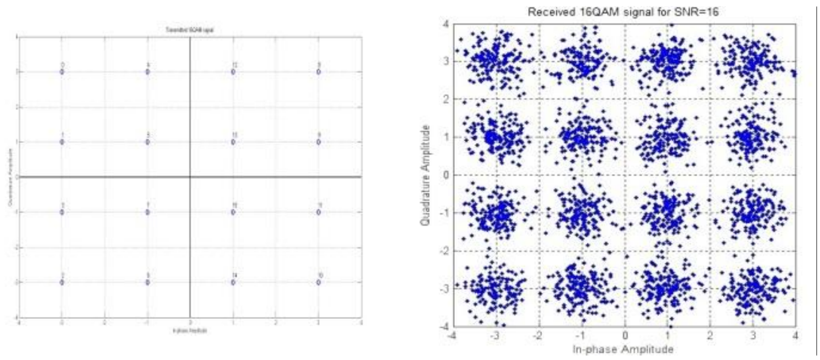

Fig5. *Transmitted16QAM signal and received 16QAM constellation for SNR = 16 dB*

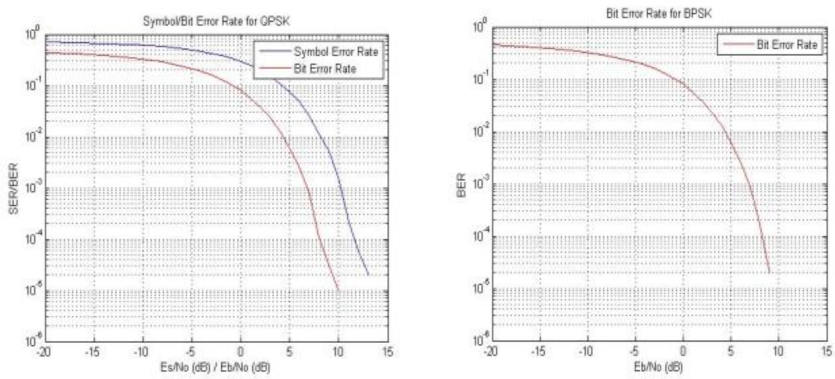

Fig6. *SER/BER representation for QPSK and BPSK modulation*

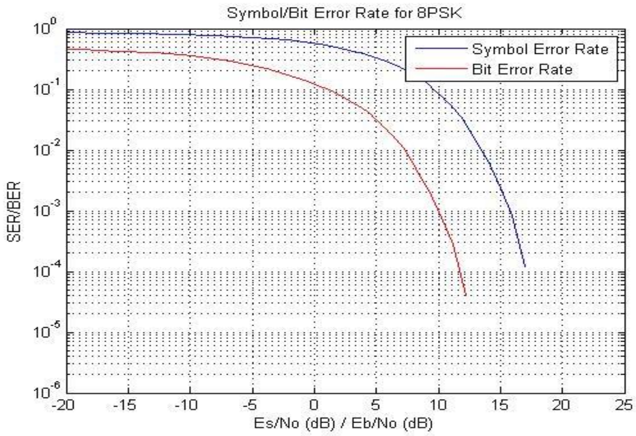

Fig7. *SER/BER representation for 8PSK modulation*

In the third part of the simulation a wireless link numerical example was considered as follows:

- The parameters used are: Cb (channel bandwidth), Dr (bit rate), Pr/No=EbDr/No=EsSr/No (power received/noise spectral density), PB (bit errorrate), PE (probability of error), Sr (symbol rate), Es (Energy of symbol), Eb (Energy of bit).
- Choosing a value for Cb=30MHz, Dr = 50 Mbit/second, Pr/No=80dB-Hz and PB required<1e-3; Dr>Cb, therefore the channel is band limited and requires MPSK scheme.
- Assigning M=4 (QPSK), Sr = Dr / (log2M) = 50 Mbits/sec/2=25 Msymbols/sec < Cb (30Mhz).
- Sr/No=(log2M)Eb/No=log2M(Pr/NoDr)=2*(10*exp8/50e6)=4=6.02dB.
- Eb/No=Pr/NoDr=(10exp8/50e6)=2=3.01dB.
- PE(M=4)=Q(sqrt(2*Sr/No)*sin(pi/M))=Q(sqrt(8)*0.3826)=Q(1.074) .

  where Q(x)=.5*erfc((x)/sqrt(2)).
- PE(M=4)=.5*erfc(1.074/sqrt(2))=4.1e-3.
- PB=PE(4)/log2M=4.1e-3/2=2.05 e-3.

Therefore, QPSK modulation isn't enough for this particular case because the probability of error didn't meet the required value of < 1e-3. Thus, the modulation that needs to be used to meet the required value is M=8 $\cong 1e - 4$ for this particular case (8PSK).

Finally, system capacity variation with SNR and Eb/No for different modulations was computed.

Considering the figures below it can be concluded that the channels capacity increases with the number of input bit streams used for representing the original signal.

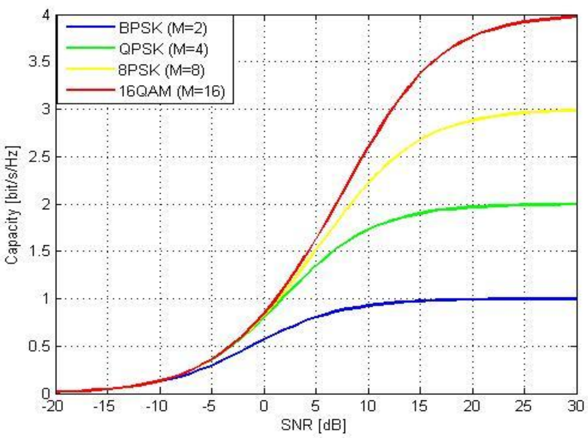

Fig8. *Rayleigh channel capacity variation with SNR*

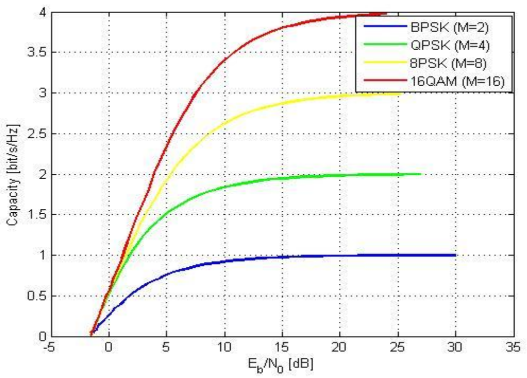

Fig9. *Rayleigh channel capacity variation with Eb/No*

5. Conclusion

In this paper a comparative performance analysis of different digital modulation schemes has been performed and can be concluded that the selection of a digital modulation is dependent on the type of the application. Each modulation scheme has advantages and disadvantages regarding the design complexity of the modulator and the demodulator, economic reasons whether BER performances can be neglected or not. Once with the evolution of telecommunication systems, higher data rates takes lead and thus parameters like BER and ISI become very important for any future digital modulation technique.

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