MODULATION SCHEMES FOR WIRELESS ACCESS

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Abstract

Four modulation schemes, namely minimum shift keying (MSK), Gaussian minimum shift keying (GMSK), multiamplitude minimum shift keying (MAMSK) and π/4 differential quadrature phase shift keying (π/4-QPSK) are described and their applicability to wireless access is discussed in the paper. Low complexity receiver structures based on differential detection are analysed to estimate the performance of the modulation schemes in the additive Gaussian noise and the Rayleigh and Rice envelope fast fading channel. The bandwidth efficiency is calculated to evaluate the modulation schemes. The results show that the MAMSK scheme gives the greatest bandwidth efficiency, but its performance in the Rayleigh channel is rather poor. In contrast, the MSK scheme is less bandwidth efficient, but it is more resistant to Rayleigh fading. The performance of π/4-QPSK signal is considerably improved by appropriate prefiltering.

Keywords

modulation, receiver, Rayleigh and Rice envelope fast fading channel, wireless access

1. Introduction

Efficient use of laptops, palmtops and notebooks requires high quality wireless access mechanisms for data and voice connection between portable and fixed devices. Inexpensive and uncomplicated infra red links (IrDA) are usually used for portable device connection. However, the infra red link has many drawbacks which limit its application in a modern wireless office. There are three serious disadvantages: limited range, obligatory line of sight connection and the fact that connection can be established between only two devices. Due to the limitations of the infra red link, the radio frequency transmission technique is more and more frequently used for short-range wireless portable device interconnections.

Initially, digital communication systems, designed for voice communication, were adopted for data communication. An example of such a system is DECT, where the latest standards and available products support both data and voice communication. The supported data rate is comparable to ISDN basic rate access. However, the DECT multiple access schemes are not suitable for simple ad hoc connection between portable devices.

A second possibility is to specify an independent system, designed only for wireless computer networks, and to standardise it. The ETSI (European Telecommunications Standard Institute) set up a group to investigate radio LANs with a throughput greater than 1Mbit/s called HIPERLAN. The two frequency bands allocated for HIPERLAN are 5.15GHz-5.30GHz and 17.1GHz-17.3GHz. The first products are already available.

A further possibility is to use the frequency bands already allocated for public use, where the device transmitted power and the channel frequency band are standardised. The major manufacturers of computer and wireless devices have chosen this option and launched the new radio frequency device for ad hoc connection between different devices. The system is called Bluetooth. The ISM (industry, science and medicine) frequency band at 2.45GHz has been chosen for system operation. The chosen modulation technique is Gaussian shaped frequency shift keying with a normalised Gaussian filter bandwidth of 0.35. The target data rate is 1Mbit/s.

It is expected however that the specified data rate will not be sufficient to support multimedia services, which require higher data throughput. The transmitted power and the frequency band are limited in the ISM band. One possible way to increase the data throughput is to use a more bandwidth efficient modulation technique.

In the following we shall compare four modulation techniques (MSK, GMSK, π/4-QPSK and MAMSK) which are suitable for short range wireless access.

The chosen modulation schemes are first described. The modulated signals are then analysed in the frequency domain followed by description of the receiver structures. The signal performance in the additive Gaussian noise channel and in the indoor environment is reported and finally the main characteristics of the analysed modulation schemes are summarised and compared.

2. The signal description

Each modulated signal $s(t)$ is described by

$$s(t) = \mathrm{Re}\{u(t)\exp(j2\pi f_c t)\} \quad (1)$$

where $u(t)$ is the base band signal and f_c is the carrier frequency. For subsequent analysis, the baseband description of the signal is sufficient.

2.1 Continuous phase modulated (CPM) signals

The first two modulation schemes (MSK and GMSK) are classified as continuous phase modulation schemes (CPM) described by

$$s(t) = \mathrm{Re}\left\{\sqrt{\frac{2E}{T}}\exp\left(j\left(2\pi f_c t + \Phi(t,a_i)\right)\right)\right\} \quad (2)$$

E is the average signal energy and T is the symbol interval. The signal phase $\phi(t,a_i)$ depends on the modulation index h, the arbitrary initial phase ϕ_0, the frequency pulse shape $g(t)$ and the input data stream $\{a_i\}$ and is given by

$$\Phi(t,a_i) = 2\pi h \sum_{i=0}^{k} a_i q(t - iT) + \phi_0 \quad (3)$$

where

$$q(t) = \int_0^t g(\tau)d\tau .$$

2.1.1 MSK signal

The MSK (minimum shift keying) signal is a CPM signal with modulation index $h=1/2$ and one bit interval rectangular frequency pulse shape $g(t)$. The baseband equivalent of a MSK signal is described by equation (4).

$$u(t) = \sqrt{\frac{2E}{T}}\exp j\left(\pi\frac{t}{2T}a_i + \phi_0\right) \quad (4)$$

The binary input signal is plotted in Figure 1, and the constellation diagram and the in-phase component of MSK signal are in Figure 2.

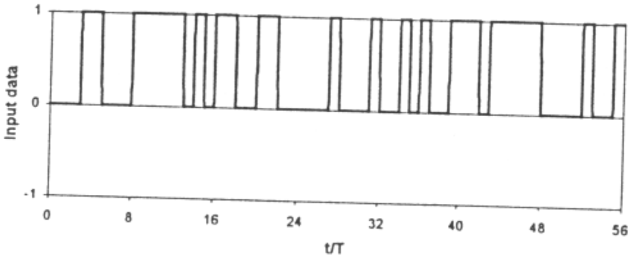


Figure 1: Input data

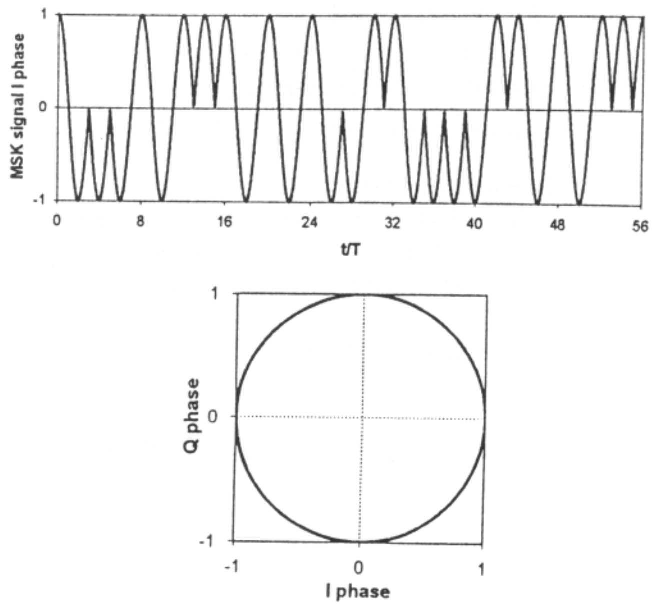


Figure 2: MSK signal I-phase component and MSK signal constellation diagram

2.1.2 GMSK signal

The GMSK signal is an MSK signal with Gaussian shaped frequency pulse defined by equation (5).

$$g(t) = \frac{1}{2T}\left[Q\left(2\pi B_b \frac{t - T/2}{\sqrt{\ln 2}}\right) + Q\left(2\pi B_b \frac{t + T/2}{\sqrt{\ln 2}}\right)\right] \quad (5)$$

$$Q(t) = \frac{1}{\sqrt{2\pi}}\int_t^{\infty}\exp(-\frac{u^2}{2})du$$

B_b is the 3dB bandwidth of a low pass Gaussian filter, T is the symbol period and the $B_N = B_b T$ is the normalised 3dB bandwidth. The normalised bandwidth $B_N = 0.35$ was chosen for the Bluetooth system. The I-phase component of the GMSK signal and the GMSK constellation diagram are plotted in Figure 3.

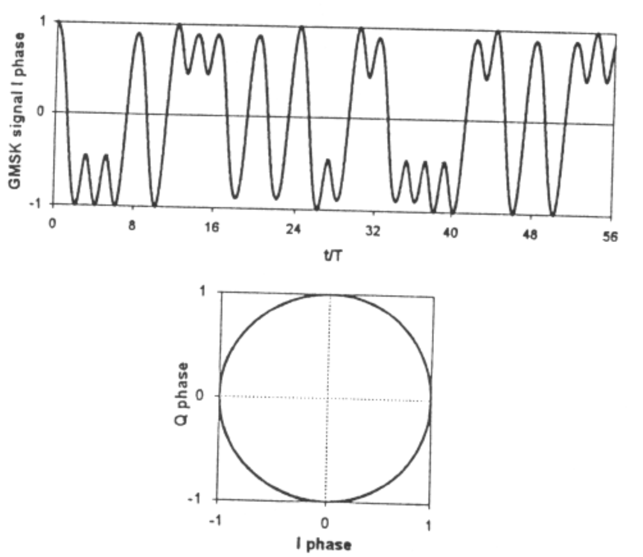


Figure 3: I-phase component of GMSK signal and GMSK signal constellation diagram

2.1.3 MAMSK signal

An MAMSK signal is obtained by summing up two MSK signals with different amplitudes:

$$s_{MAMSK}(t) = s_{MSK1}(t) + 2 * s_{MSK2}(t) \quad (6)$$

The baseband MAMSK signal can also be expressed as a product of variable signal envelope *r(t)* and signal phase *Φ(t)*. The mathematical expressions for signal envelope *r(t)* and signal phase *Φ(t)* are given in equations (7), (8), (9).

$$u(t) = r(t)\exp(j\Phi(t)) \quad (7)$$

$$r(t) = \sqrt{\frac{2E}{5T}\{5 + 4\cos[(\phi_1(t, a_{i1}) - \phi_2(t, a_{i2})) + \phi_0]\}} \quad (8)$$

$$\Phi(t) = \arctan\left[\frac{\sin(\phi_1(t, a_{i1})) + 2\sin(\phi_2(t, a_{i2}) + \phi_0)}{\cos(\phi_1(t, a_{i1})) + 2\cos(\phi_2(t, a_{i2}) + \phi_0)}\right] \quad (9)$$

where ϕ_0 is the phase difference between the lower and upper components of the MAMSK signal at time *t=0*. The I-phase component of the MAMSK signal and the MAMSK constellation diagram are shown in Figure 4.

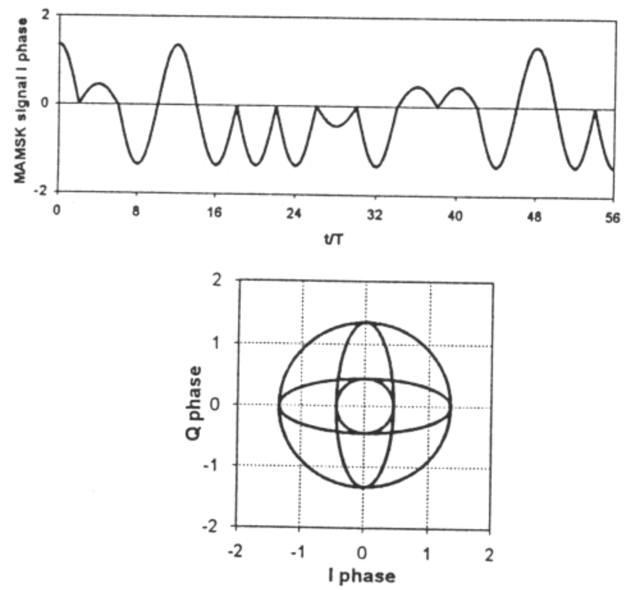


Figure 4: I-phase component of MAMSK signal and MAMSK signal constellation diagram

2.1.4 π/4-QPSK signal

The π/4-QPSK modulation scheme is a special case of the QPSK modulation scheme where the signal phase shift depends on the input data (two bits) and the current signal phase. The baseband equivalent of the π/4-QPSK signal is described formally by equations (10), (11) and (12).

$$u(t) = \frac{E}{2T}\sum_{n=0}^{k/2-1}\cos(\theta_n)g(t-nT) + j\sin(\theta_n)g(t-nT) \quad (10)$$

$$\theta_n = \theta_{n-1} + \phi_n \quad (11)$$

$$\phi_n = \begin{cases} \frac{\pi}{4} & a_i = 0 \quad a_{i+1} = 0 \\ \frac{3\pi}{4} & a_i = 1 \quad a_{i+1} = 0 \\ \frac{5\pi}{4} & a_i = 1 \quad a_{i+1} = 1 \\ \frac{7\pi}{4} & a_i = 0 \quad a_{i+1} = 1 \end{cases} \quad (12)$$

E/2T is the signal amplitude, θ_n and θ_{n-1} are phases of the *n*th and *(n-1)*th symbol intervals respectively and *k* is the number of bits sent. The I-phase component of π/4-QPSK signal and the π/4-QPSK constellation diagram are plotted in Figure 5.

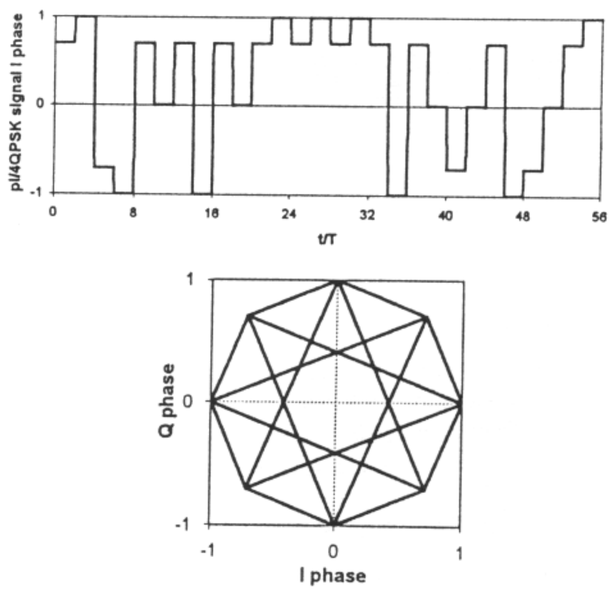
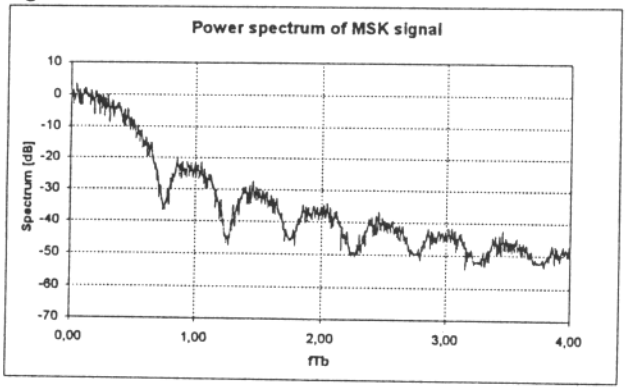


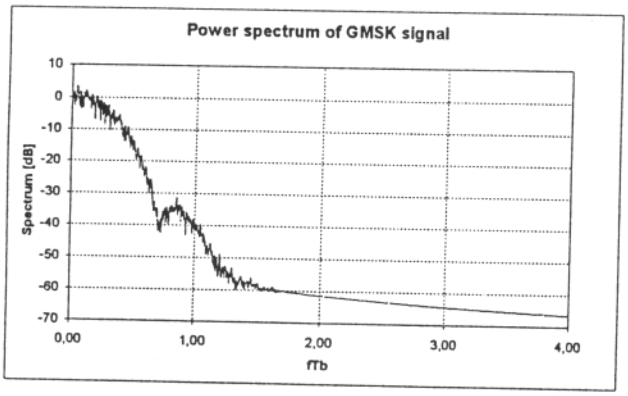
Figure 5: I-phase component of π/4-QPSK signal and π/4-QPSK signal constellation diagram

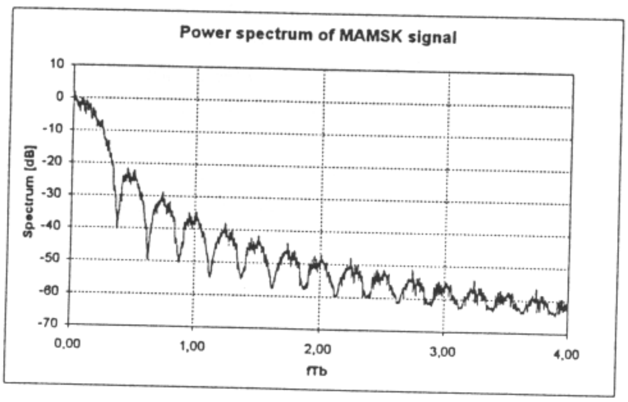
The signal envelopes are seen in the constellation diagrams. The MSK and GMSK signals have constant envelopes, while the MAMSK signal and π/4-QPSK signal envelopes are time variable. The signal envelope variation has a great impact on signal distortion, if a nonlinear amplifier is used as a high power amplifier in the transmitter

3. Power spectrum density

The bandwidth efficiency of the signal is a very important factor in assessing modulation schemes in a band limited communication system. The number of bits transmitted in a Nyquist bandwidth is an appropriate feature for defining bandwidth efficiency if the linear modulation schemes are being analysed. However, such a definition is not appropriate for nonlinear modulation schemes. In this cases the fractional out of band power is used to calculate the bandwidth efficiency of the nonlinear signal.







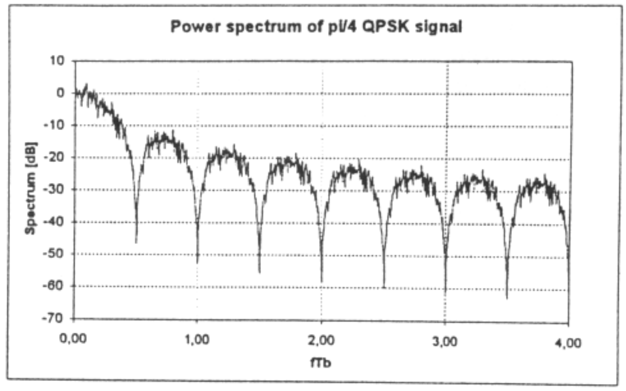


Figure 6: Signals power spectrum

The power spectra of the analysed signals are plotted in Figure 6 and fractional out of band power shown in Figure 7. *fTb* is the normalised frequency, *Tb* is the period of one transmitted bit and *f* is frequency. If the fractional out of band power is analysed at a normalised frequency *fTb=0.5*, the MAMSK signal outperforms GMSK, MSK and π/4-QPSK signals. On the contrary, at normalised frequency *fTb=1.0* the GMSK signal outperforms other signals. Gaussian pulse shaping greatly reduces the fractional out of band power of the GMSK signal. The adjacent channel interference of all analysed signals can be improved by the signal prefiltering. In the case of π/4-QPSK modulation the spectral characteristics can be improved by placing a square root raised cosine filter in the transmitter. A square root raised cosine filter at the receiver side of the system increases the signal to noise ratio.

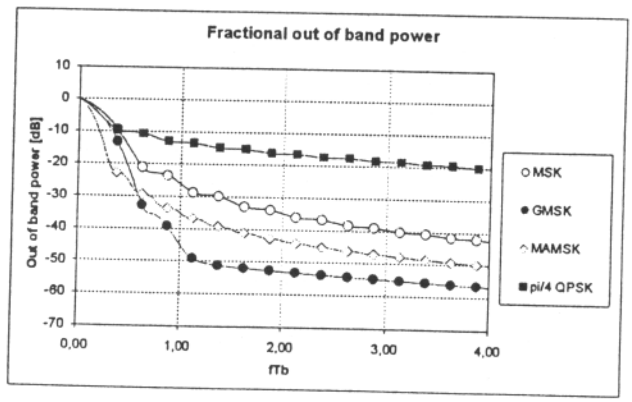


Figure 7: Signals out of band power

4. Receiver structures

A simple receiver structure should be used in wireless communication system for two main reasons:

- the power consumption of a portable terminal and
- the price of the portable terminals.

Simple differential receivers are analysed. In the first stage of the receiver, the noisy received signal is filtered.

After filtering, the receiver structure depends on the modulation scheme.

Identical receivers are used for MSK and GMSK modulation schemes. The received signal $r(t)$ is first filtered by a receiver filter. The differential detector multiplies the filtered signal $r_F(t)$ by a one bit interval delayed and conjugated version of the same filtered signal $r_F(t-T)^*$. If the second harmonic component of the product is filtered out, the remaining signal consists of the phase difference in the successive bit intervals and the changes in the phase corrupted by Gaussian noise. The signal is sampled when the eye opening has a maximum value. The samples are first compared. After hard detection, the estimation of the transmitted data is made. The receiver structure is shown in Figure 8.

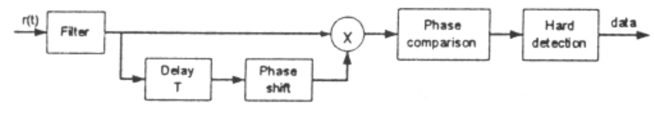


Figure 8: GMSK and MSK receiver structure

The MAMSK differential receiver is described in Figure 9. The receiver is based on the following facts:

- The MAMSK signal phase depends only on the MSK signal with higher amplitude. The even transmitted bit is detected only from the MAMSK signal phase.
- The MAMSK signal envelope variation depends on the difference between the two MSK component phase rotations. If there is no significant amplitude variation in the succeeding bit interval, the odd transmitted bit is equal to the even. In the case of an amplitude difference, the odd transmitted bit is the negative value of the even transmitted bit.

The receiver structure is shown in Figure 9. The lower part is a differential phase detector and the receiver upper part is a differential amplitude detector.

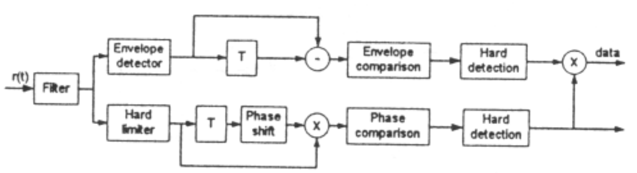


Figure 9: MAMSK receiver structure

There are three types of noncoherent detection proposed in the literature for π/4-QPSK modulation schemes, namely baseband differential detection, IF-band differential detection and FM discriminator type detection. The performances of all three types are nearly the same if optimal filtering is implemented in the receiver. The baseband differential detector is used in our simulations. The π/4-QPSK differential detector is shown in Figure 10. Detection is achieved by multiplying the received signal by its delayed version (one symbol interval), followed by hard detection.

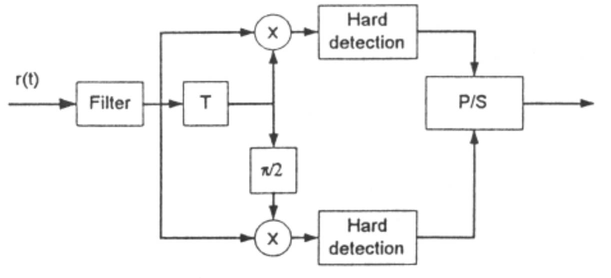


Figure 10: Differential π/4-QPSK detector

5. Signal performance degradation due to Gaussian noise

Every communication system is affected by noise generated by the thermal movement of electrical particles. The frequency spectrum of the additive noise is flat. The noise amplitude is a random variable and obeys a Gaussian distribution. The main part of the Gaussian noise is generated in the receiver.

Taking into account all the described facts, the modulation schemes are tested in the Gaussian channel. The π/4-QPSK signal is shaped at the transmitter by a square root Nyquist filter with roll off factor $\alpha=1.0$. The receiving filters in all the systems are normalised to one bit time interval and the receiving filters are square root Nyquist filters with roll off factor $\alpha=1.0$. The results obtained are plotted in Figure 11. The π/4-QPSK and MSK modulation schemes perform similarly in the Gaussian channel. The MSK modulation scheme outperforms π/4-QPSK by only 1 dB. The MAMSK modulation scheme is more sensitive to Gaussian noise due to lower normalised Euclidean distance. If a filter with broader bandwidth is used, the results for GMSK signal are better.

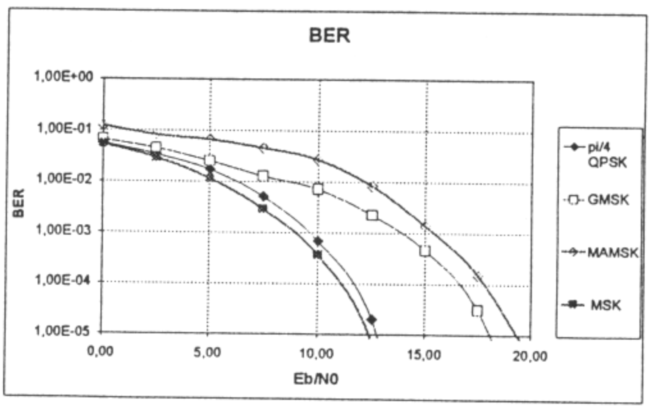


Figure 11: Modulation signal performance in the Gaussian channel

6. Signal performance degradation due to indoor radio channels

Besides Gaussian noise, which is generated mainly at the receiver, the transmitted signal is strongly affected by the environment surrounding the transmitter and the receiver. Indoors, the transmitted signal is reflected from different obstacles. The reflected signals arrive at the receiver via different paths with different phases, amplitudes and delays. The indoor radio channel can be described by two fading mechanisms: long term fading, which has log-normal distribution and short term fading which follows Rayleigh or Rice distribution. Short term fading causes the signal envelope variation at the receiver. If the level of movement is low and if the receiver and transmitter are in line of sight, fading follows the Rice distribution with K=7-14 dB. In an environment with no line of sight, the fading follows Rayleigh distribution.

The signals are also analysed in a short term fading environment. The analysed signal performance in a Rayleigh fading environment is plotted in Figure 12. If the results for the Gaussian channel and for the Rayleigh fading channel are compared, a degradation of 2 dB is observed for GMSK, MSK and π/4-QPSK signals. The MAMSK receiver performance is unsatisfactory, because the even transmitted bits are detected from the signal envelope variation.

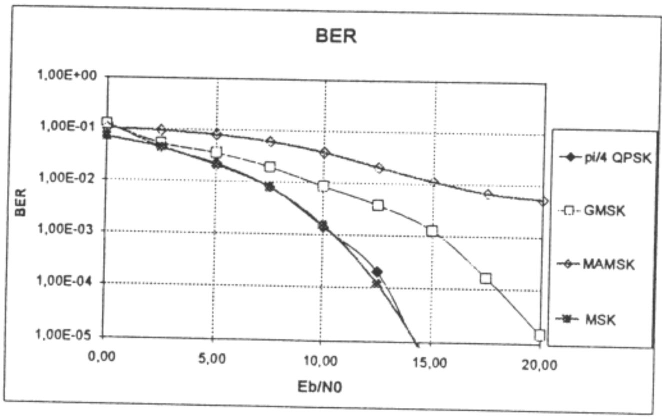


Figure 12: Modulation signal performance in Rayleigh fading channel

The performance of the MSK, GMSK and π/4-QPSK modulation schemes in a Rayleigh fading channel is close to that in a Gaussian channel; therefore only the MAMSK signal performance is analysed in the Rice fading channel. The results of the MAMSK modulation scheme are plotted in Figure 13. If the power of the dominant radio signal path K is 7.5 dB above the reflected radio paths, the MAMSK signal is degraded by 2 dB compared to the Gaussian channel.

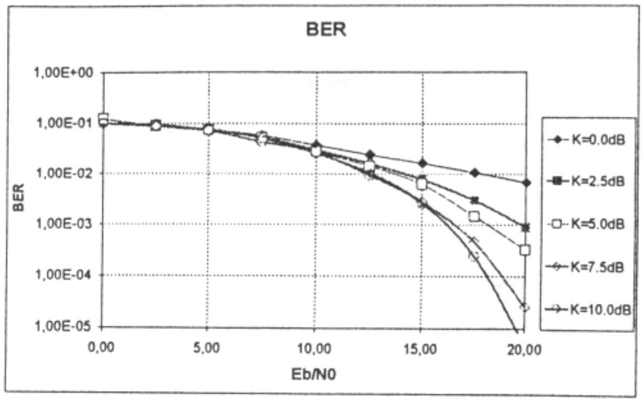


Figure 13: MAMSK signal Rice channel

7. Conclusion

Four modulation schemes suitable for indoors wireless access have been analysed. The analysis was focused on the signal spectral efficiency and on the signal degradation due to additive Gaussian noise and to signal envelope fast fading which follows Rayleigh or Rice probability density functions.

The bandwidth efficiency of the modulation schemes has been analysed by calculating the normalised frequency bandwidth where 99% of the signal energy is transmitted. The results are summarised in Table 1. The unfiltered π/4-QPSK exhibits the poorest performance. The signal power is spread wide across the frequency band. If the π/4-QPSK signal is filtered by a square root Nyquist filter, the bandwidth of the π/4-QPSK is nearly two times wider than that of the MSK signal.

	MSK	GMSK	MAMSK	π/4-QPSK non-filtered	π/4-QPSK filtered
fT_{99}	0.64	0.32	0.32	∞	1.0

Table 1: Normalised bandwidth fT_{99} where 99% of the signal energy is transmitted

BER=10^{-3} was chosen for analysis of the power efficiency of the modulation schemes in the AWGN channel. If the signal-to-noise ratio (E_b/N_0) is greater than 9 dB then the BER of the MSK signal is lower than 10^{-3}. An additional 1 dB of signal power is needed for π/4-QPSK signal, 5 dB for GMSK signal and 7 dB for MAMSK signal to achieve the same BER=10^{-3}.

When the signal is analysed in the fading channel with the envelope following the Rayleigh probability density function, signal performance degradation of 2 dB is observed for MSK, GMSK and π/4-QPSK signals. The MAMSK differential receiver is not suitable for a Rayleigh fading channel. If the signal envelope fading follows Rice distribution with K>7.5 dB, BER for the MAMSK signal is lower than 10^{-3} if the E_b/N_0 is greater than 16.5 dB.

The bandwidth efficiency of the modulation signal can be improved by prefiltering with carefully designed transmitter filters. The signal power efficiency can be improved by designing more complicated receiver structures and optimal signal postfiltering at the receiver part of the system.

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