Error Rate Analysis of Broadband Binary FM in an Indoor Channel

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The emerging 5GHz unlicensed bands in Europe and the US may be used to support short range, high rate links for portable computers. This would overcome the range and directionality limitations of today's infrared connections. This paper investigates the performance of a binary FM link in this application, operating in a dispersive indoor channel. The consequence of increasing the modulation index is explored as a cost free means of multipath mitigation.

An increase from 0.5 (MSK) to 1 was found to yield a worthwhile improvement in tolerable delay spread. Increasing the index beyond 1 gave no further improvement but significantly affected the spectral occupancy of the signal. This defines a precise design point for high rate, short range radios.

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Abstract - The emerging 5GHz unlicensed bands in Europe and the US may be used to support short range, high rate links for portable computers. This would overcome the range and directionality limitations of today's infra-red connections. This paper investigates the performance of a binary FM link in this application, operating in a dispersive indoor channel. The consequence of increasing the modulation index is explored as a cost free means of multipath mitigation. An increase from 0.5 (MSK) to 1 was found to yield a worthwhile improvement in tolerable delay spread. Increasing the index beyond 1 gave no further improvement but significantly affected the spectral occupancy of the signal. This defines a precise design point for high rate, short range radios.

1. Introduction

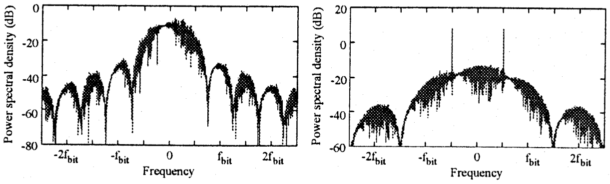
At present, ad-hoc interconnects for mobile computers are provided by infra-red equipment operating at up to 4Mbps. This is sufficiently inexpensive that it can be provided as a standard feature of mobile computers. However it has range and directionality limitations which are difficult to overcome. Radio resolves the range and usability problems, but at a price. It is necessary to find an architecture which is sufficiently inexpensive for pervasive deployment to occur.

The operating environment of this application is unlike that of today's radio systems. Consequently, the design objectives of the radio must be equally different. Current radio standards aim to maximise the number of users in a given geographic area, this is true of both local and wide area systems. This leads to a desire to maximise the bandwidth efficiency of the systems. Because of the extreme low power of this application, interference from adjacent systems is small and hence, the frequency re-use is efficient. This makes bandwidth efficiency less important. Instead, this application demands an inexpensive radio transceiver architecture which will give satisfactory performance in a dispersive fading environment.

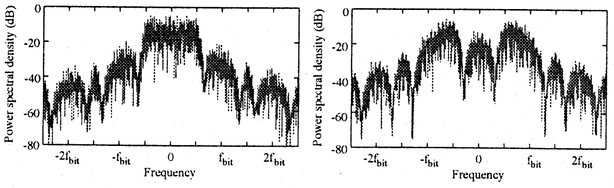
Binary FM is a modulation scheme which can be generated and received using a very simple transceiver. This makes it attractive for use in this application. A typical transceiver would employ a synthesized transmitter with closed loop modulation and a single IF superheterodyne limiter-discriminator receiver. The transceiver is required to operate in a frequency selective fading environment. It is usual to chose a modulation index of 0,5 (MSK) as this is the closest tone spacing which still achieves orthogonal signalling states. MSK is generally used because of its superior bandwidth efficiency, however this is less important in this application. Consequently, it becomes interesting to consider the effect of increasing the modulation index of the binary FM on the error performance of the link in a dispersive fading channel.

2. Spectral Occupancy

Increasing the modulation index broadens the spectral occupancy of the transmitted signal. In the case of MSK, 99% of the transmitted energy is constrained within a bandwidth equal to 1,5 times the bit rate. For binary FM with an modulation index of one, 94% of the transmitted energy is constrained within this bandwidth.



Modulation index = 0.5 (MSK) **Modulation index = 1**



Modulation index = 0.7 **Modulation index = 1.4**

Figure 1. Transmitted spectra of Binary FSK.

Many radio system specifications control spectral occupancy by defining a limit on the power which may be transmitted in a 1MHz bandwidth, relative to the total transmit power at a number of offset frequencies from the centre of the channel. In order to quantify the effect of broadening the modulation index, this measurement has been performed for each of the cases of binary FM shown in Figure 1 and compared with the limits set by the HIPERLAN standard. This illustrates the modulation index which can be reached before the allowable transmitted power mask defined by the HIPERLAN standard is broken. HIPERLAN was chosen as a reference standard as it is a high rate system which uses an FM based modulation format. From this, the following conclusions may be drawn about the channel spacing and transmit power mask required to allow a modulation index of one to be accommodated:

i) The power measurements demonstrate that a binary FM transmission with $m_f > 0,5$ breaks the allowable power mask defined by the HIPERLAN standard in the $15 < |f\text{-}fc| < 25$ MHz region. When establishing a power mask for new bands, such as the emerging 5GHz NII band in the US, it would be wise to ensure a transmitted power mask is defined which can accommodate a binary FM transmission with $m_f > 1$.

ii) HIPERLAN has channel spacing at the bit rate. A binary FM system with a modulation index of 1 would not fit into this channel spacing as the tones at +/- the signalling frequency of adjacent channels would overlap. Channel spacing of 1,5 times the bit rate, as used by DECT would be satisfactory.

TABLE I

Modulated power in 1MHz for binary FM

Normalised frequency range	Allowable power in 1 MHz for HIPERLAN [1]	Max power in 1 MHz $m_f = 0,5$	Max power in 1 MHz $m_f = 0,7$	Max power in 1 MHz $m_f = 1$	Max power in 1 MHz $m_f = 1,4$
0 < f <0.425	0 dB	-11 dB	-14 dB	-17 dB	-20 dB
0.43 < f <0.51	-5dB	-19 dB	-13 dB	-6 dB	-14 dB
0.51 < f <0.64	-10 dB	-23 dB	-18 dB	-20 dB	-14 dB
0.64 < f <1.06	-22 dB	-33 dB	-31 dB	-21 dB	-12 dB
f> 1.06	-33 dB	-37 dB	-36 dB	-29 dB	-25 dB

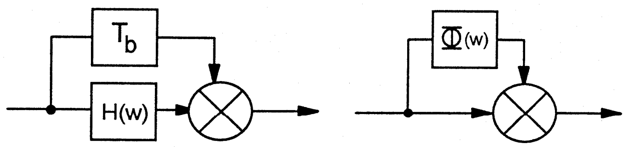
Notice in the $m_f = 1$ case the presence of tones at +/- the signalling frequency. They contain half the power of the transmitted signal but no information is transmitted in the tones. Their presence ensures the modulated carrier has a constant amplitude.

3. Receiver Architectures

Several architectures may be used to receive a binary FM signal. These include coherent, differential and discriminator structures. It is interesting to consider which of these architectures is most appropriate in this short range, high rate application. The receiver cost and dispersive fading performance are the critical factors affecting the choice of architecture.

The performance of the receiver in a dispersive fading channel is significant as the dominant error mechanism in this link is signal distortion caused by time dispersion in the channel. The performance of these receivers is well understood in AWGN and narrow band fading channels [2], [3]. In dispersive fading, a rule of thumb is that conventional modems will work up to rms delay spreads equal to 10% of the bit period [4]. However, performance differences exist between the different types of receiver.

Coherent reception was discounted because estimating the received carrier phase in a selective fading channel adds complexity and cost to the receiver, which is inappropriate in this application. The architectures considered were the differential and frequency discriminator receivers shown in figure 2.



1-bit differential detector

Frequency discriminator

Figure 2. Non-coherent receivers for binary FM.

The binary FM signal can be described by equation (1)

$$s_{rx} = \cos(w_c.t + \phi(t)) \qquad (1)$$

Where w_c is the carrier frequency. The modulating signal, $\phi(t)$ is generated by integrating the NRZ data to be transmitted. In the differential detector, the filtered output of the phase comparator mixer is given by equation (2)

$$v_{out}(t) = \sin(\phi(t) - \phi(t - T_b) + w_c.T_b) \qquad (2)$$

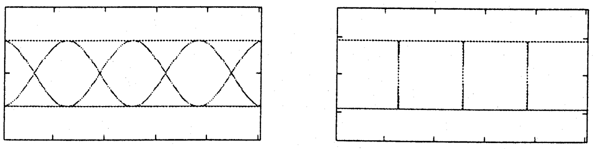
Where T_b equals one bit period. The differential detector requires a Hilbert transform, H(w) if $w_c.T_b$ is chosen as an integer multiple of $2.\pi$ radians. The bit rate and carrier frequency are usually chosen so this relationship is true to allow the data stream and carrier to be generated using the same system clock. The Hilbert transform would not be needed in one branch of the receiver if $w_c.T_b$ was chosen to be $2.\pi + \frac{\pi}{2}$ radians.

In the discriminator detector, one branch of the phase detecting mixer is driven by the incoming signal. The other is driven by a phase shifted version of that signal. The phase shift circuit has a phase response, $\Phi(w)$. This provides a phase gradient from 0 to 180 degrees about the carrier frequency. A phase shift which is proportional to the instantaneous frequency of the incoming signal is generated. This is detected by the mixer. Equation (3) describes the voltage seen at the output of the mixer:

$$v_{out} = \cos\left(w_c.t + \phi(t) + \Phi\left(\frac{d}{dt}(w_c.t + \phi(t))\right)\right) \quad (3)$$

$$v_{out} = \cos(\Phi\left(w_c + \frac{d\phi}{dt}\right)) \quad (3)$$

Figure 3 shows the eye diagrams for the differential and discriminator receivers for a transmitted signal with no premodulation filtering. The differential detection process has led to a closing of the received eye. This degradation becomes more critical when the channel introduces dispersion through premodulation filtering and multipath activity. As the differential receiver compares the present bit with the preceding bit, the decision is based on the angle between two vectors, both of which are subject to dispersion induced error. In the discriminator receiver, the softwave is proportional to the instantaneous frequency of the incoming signal so the receive decision is based on the angular speed of the received vector at only one point in time, making it less prone to dispersion induced error. This qualitative assessment suggests that the discriminator receiver will have better performance in dispersive fading than the differential receiver. Equally, because of the eye closure, it is probable that the differential receiver will be more sensitive than the discriminator receiver to the performance of the bit timing recovery circuit.


Differential receiver

Discriminator receiver

Figure 3. Received binary FM eyes over an ideal channel.

The discriminator receiver also appears to be more attractive for implementation reasons. The differential detector requires a delay of one bit period. The bit period is too high to be simply realised in an analogue fashion. Equally, a digital implementation would be more expensive than the discriminator receiver.

4. Simulation

The simulation investigated the irreducible error rate introduced by dispersive fading. A quasi-stationary channel model was used. The channel power delay profile had an exponential decaying response [5]. This is characterised by equation (4):

$$P(t) = \exp\left(\frac{-t}{\tau}\right) \quad (4)$$

τ = Multipath decay constant. This represents a time averaged received power delay profile, which was then sampled into several bins each of which was multiplied by a random variable with a Rayleigh magnitude and uniform phase distribution, simulating the effect of wideband fading. The random variables change with each transmitted packet. This quasi-stationary channel assumption is valid as Doppler at in-building rates with a carrier frequency lower than 5 GHz has negligible effect across a 10ms data packet.

In the simulation, the optimum bit sampling point for each packet was determined by measuring the BER at all possible timing points and choosing the lowest error rate. This simulates the behaviour of a correlator based timing recovery mechanism.

The simulation results are shown in Figure 4. A differentially received MSK simulation was performed to compare the results with the GMSK B_bT = 0,5 simulation in [4]. As expected, there is good correlation between these as Gaussian filtering of this tightness adds insignificant dispersion when compared with the channel.

A significant improvement in delay spread performance is achieved by increasing the modulation index from 0,5 to 1. However, increasing the modulation index beyond 1 yields no apparent improvement in performance. This may be explained by considering the received signal in the IQ plane. Irrespective of the modulation index, the signal is composed of a wanted vector and an unwanted interfering vector arriving via a delayed ray from the preceding symbol. Inter-symbol interference will occur when the preceding symbol was different to the present symbol. This generates an interfering vector rotating counter to the wanted vector. If the modulation index is one, the wanted vector rotates through 180 degrees during a symbol period. Equally, the interfering vector rotates through 180 degrees in the other direction. This ensures all possible resultant vector angular velocities have been generated within the symbol period.

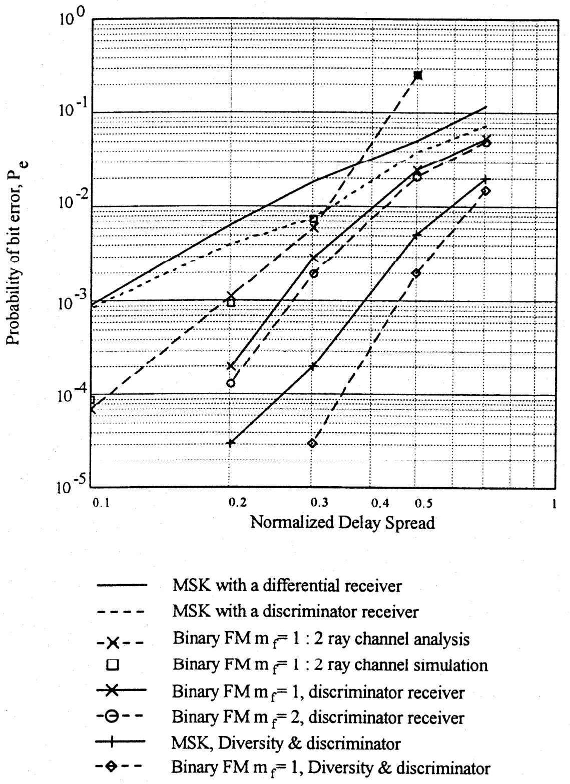


Figure 4. Simulated delay spread performance.

If the modulation index is raised to two, then the wanted vector will circle the IQ plane entirely. The interferer will circle the wanted vector twice, so the vector trajectory will repeat itself producing twice as many points within the symbol where the angular velocity is optimal for sampling. This will yield no improvement in error rate as only one optimum sample point is needed. However, in the case of MSK, the wanted symbol and interferer rotate through just 90 degrees in the IQ plane. This does not generate all potential resultant angular velocities for that channel within one symbol, so the optimum resultant velocity is not always present in the symbol. Example simulated received softwaves for a normalised delay spread of 0,6 are shown in figure 5.

In addition, two branch switched diversity was found to yield a significant performance improvement in both systems. Using received signal strength as an indication of channel quality was found to be effective even in the dispersive fading channel.

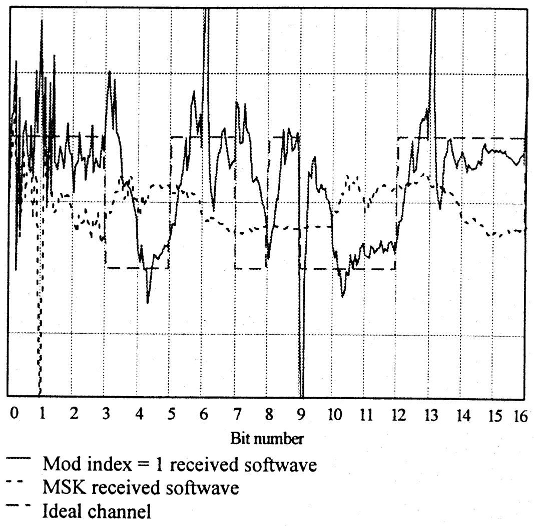


Figure 5. Example simulated received softwaves, channel rms delay spread = 0,6.

5. Analysis

To further illustrate the error mechanism which is alleviated by increasing the modulation index consider the following analysis. The transmitted signal is given by :

$$s_{tx}(t) = \cos(w_c t + \phi(t)) \qquad (5)$$

Where $\phi(t)$ is a linear phase rotation of $\pm\frac{\pi}{2}$ rad for MSK or $\pm\pi$ rad for $m_f = 1$ within a symbol period. Expressing this signal in complex baseband form and convolving it with a two ray channel model gives the signal at the input to the discriminator:

$$s_{rx}(t) = e^{j\phi(t)} * [r_1.\delta(t) - a.r_2.\delta(t - T_b)] \qquad (6)$$

$$s_{rx}(t) = |r_1|.e^{j[\phi(t)+\phi_{r1}]} - a.|r_2|.e^{j[\phi(t)+\phi_{r2}]} \qquad (6)$$

Where T_b is the bit period. The magnitude of the interfering ray, $0 < a < 1$ yields a normalised channel rms delay spread in the range $0 < \sigma < 0,5$. The Rayleigh random variables r_1 and r_2 model the quasi-stationary fading of the channel. Figure 6 illustrates the discriminator output signal, which is found by differentiating the argument of equation (6). In the figure, an example delayed ray magnitude of a = 0,8 is used, which yields a normalised delay spread of 0,497. It can be seen that a symbol duration of $\pm\pi$ radians is needed to guarantee reaching a point within one symbol where the received vector speed equals the wanted vector speed. If as in MSK, the phase rotates through just $\frac{\pi}{2}$ radians in a symbol, the optimum sample point will not always be reached within the symbol period.

A bit error occurs when there is a symbol transition and $a.r_2 > r_1$. Under these conditions, there is no point in the symbol with the correct vector speed. This is a harsher channel environment than that of the more realistic exponential channel model. In this, the amount of interfering energy diminishes though the symbol, reducing the magnitude of the interfering vector as the symbol progresses. In the two ray case, the size of the interfering vector remains constant throughout the symbol. This explains why the analytically derived and 2 ray channel simulated $m_f = 1$ curves have poorer performance than the simulation with the more realistic exponential channel model.

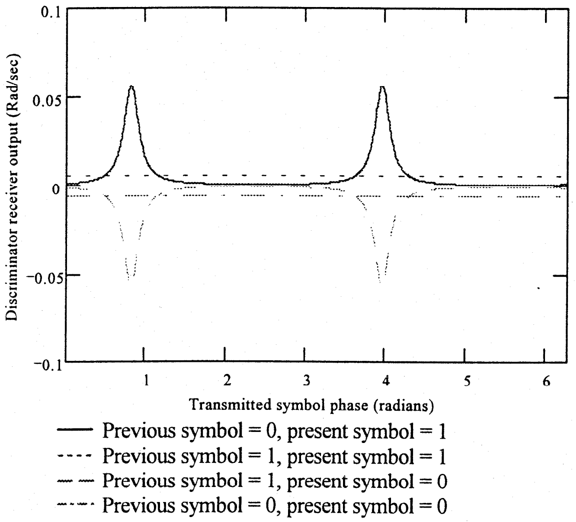


Figure 6. Discriminator output given a 2 ray channel with a = 0,8.

6. Conclusions

Radios operating in unlicensed spectrum at 5GHz could be used to provide short range, high rate data links between mobile computers. This would offer superior usability over today's infrared solutions.

Binary FM has been proposed as a suitable modulation scheme. A limiter discriminator receiver structure has been found to offer advantages in terms of implementation cost and bit error performance in a dispersive fading channel.

The effect of modulation index on the error performance of the link in a dispersive fading channel has been investigated. It has been demonstrated that a modulation index of one yields an improvement in the irreducible error rate over MSK. The MSK receiver was able to reach a normalised delay spread of 0,1 for a bit error rate of 1:1000. The binary FM, $m_f = 1$ system was able to reach a normalised delay spread of 0.27 for the same BER.

7. References

[1] HIPERLAN Functional Specification Version 1.1, PT41 & RES 10. European Telecommunications Standards Institute, January 1995, section 10.7.2.2 Emissions due to switching and modulation.
[2] Murota, "GMSK Modulation for Digital Mobile Radio Telephony, " in IEEE Transactions on Communications, COM-29, pp. 1044-1050, July 1981.
[3] T. T. Tjhung et al, "Error Rates for Narrow-Band Digital FM with Discriminator Detection in Mobile Radio Systems," in IEEE Transactions on Communications, Vol. 38, No. 7, July 1990.
[4] A. R. Nix, G. H. Norton, and J. P. McGeehan, "Error rate analysis for indoor wireless networks," in IEEE 42nd Vehicular Technology Conference, May 1992, pp. 808-813.
[5] S. Gurunathan and K. Feher, "Multipath Simulation Models for Mobile Radio Channels," in IEEE 42nd Vehicular Technology Conference, pp. 131-134, May 1992.

8. Acknowledgements

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