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Introduction

This paper discusses the relative susceptibility of both Direct Sequence and Frequency Hopped spread spectrum to interference. It is based upon, and extends, a previous analysis [1] and uses the performance of a Differential Phase Shift Keying modem as a benchmark for comparison.

The precise nature of interference in the 2.4 GHz ISM band is difficult to predict; measurements of domestic microwave ovens have shown a large degree of variation. Whilst over the long-term emissions exhibit a spectral occupancy of tens of MHz, it was found that they tend to have an instantaneous bandwidth of less than 1 MHz, but exhibit considerable frequency instability. Slew rates of up to 10 MHz/ms have been observed on some ovens, although others have been found to have relatively constant emissions over periods of several milliseconds. The peak output power measured was typically around 2 dBm.

Based upon these measurements, we have assumed in our analysis that the interference is narrowband and white noise-like, affecting k channels in the FH case and appearing wholly in-band of the despread DS signal. The presence of a given level of interference causes a degradation in the E_b/N_o at the receiver, with a resulting reduction in BER performance, which for DPSK is proportional to the exponential of the reciprocal of the effective E_b/N_o.

With the DS system, the effect of despreading is to reduce the power of a narrowband interferer by the processing gain. Thus the receiver operates in a noisy environment, defined by the current signal-to-noise ratio, modified by the interference power that arises after despreading. In the case of FH, the demodulator normally operates at the E_b/N_o determined by the relative levels of signal power and thermal noise at the input to the demodulator. On the *k* hop channels which are hit by interference, the level of noise power increases according to the signal-to-interference ratio. Thus the overall error rate is a weighted average of the error rates arising on the *N-k* good channels (where *N* is the total number of hop channels available) and the increased error rate found on the *k* hit channels.

In order to allow comparison of the performance of the two systems in terms of predicted operating range, a simple path loss model describing the propagation of the wanted signal and that of the interferer has been employed. It should be stressed that whilst the accuracy of the model used determines the absolute values of predicted range, it does not affect in any way the comparative performance of the two systems at a given level of interference power.

System Performance

The probability of bit error for DPSK is given by [2]:

$$P_{e\_DPSK} = 0.5\exp(-\{effective\ E_b / N_o\}) \tag{1}$$

where the effective E_b/N_o is determined by the ratio of the signal power to the total level of interference power and noise present at the input to the demodulator. For the DS system, the effect of despreading is to reduce the power of a narrowband interferer by the processing gain, ignoring any implementation loss in this process. Thus the effective E_b/N_o is given by:

$$effective\ E_b / N_o|_{DS} = \frac{1}{\dfrac{1}{E_b / N_0} + \dfrac{1}{SIR * B_e}} \tag{2}$$

where *SIR* is the signal-to-interference ratio appearing at the input to the receiver and B_e is the bandwidth expansion factor (processing gain) of the DS system.

In the case of FH, the demodulator operates with a probability of bit error determined by the E_b/N_o which on a clear channel is only affected by the signal-to-noise ratio. On the hop channels which are hit by interference, the level of noise power increases according to the signal-to-interference ratio. Thus the modified E_b/N_o for the FH system becomes:

$$effective\ E_b / N_o|_{FH} = \frac{1}{\dfrac{1}{E_b / N_0} + \dfrac{1}{SIR}} \tag{3}$$

From the calculated levels of interference and noise, the signal power required to achieve a given performance can be evaluated for both the FH and DS receiver. The predicted operating range can be directly inferred from this signal level, knowing the transmit power and having modelled the path loss from the transmitter to the receiver. A simple path loss model based upon the JTC model [3] for propagation in the PCS bands and translated to 2.4 GHz has been used.

The analyses employed here are based upon solving for the signal power required to meet a given quality of service, using the modified probability of bit error equations for each system. In systems where minimal coding and a simple MAC are used, the key performance metric of the physical layer is the packet error rate. In the case where no Forward Error Correction is employed, this defines the number of packets that will have to be re-transmitted and gives a measure of the throughput available.

Consider a packet of n data bits and assume that a narrowband interferer remains on-frequency for the duration of the packet. In the case of direct sequence, the probability of packet failure for a n bit packet is given by:

$$PFR|_{DS} = 1-(1-P_e|_{DS})^n \tag{4}$$

where $P_{e|DS}$ is the probability of bit error taking account of the interference reduction achieved by despreading. In the case of FH, the probability of a failed packet transmission is dependent upon the sum of the probabilities of success on a hit and on a clear channel, weighted by the probability of transmitting on each of these. Thus:

$$PFR|_{FH} = 1-\left(\frac{k}{N}(1-P_{e\_hit}|_{FH})^n + \frac{N-k}{N}(1-P_{e\_clear}|_{FH})^n\right) \tag{5}$$

where $P_{e\_hit|FH}$ is the probability of a bit error on the hit channel and $P_{e\_clear|FH}$ is that on a clear channel.

In this example we consider operation in the ISM bands specifically. According to the FCC rules (Part 15.247) [4], a frequency hopping system must employ a bandwidth expansion factor of at least 75. It is assumed that the direct sequence system utilises the minimum processing gain allowable (10 dB). In Figure 1, the performance of the two systems at various fixed levels of interference is investigated in terms of the operating range offered at varying packet failure rates. It is assumed that 5 FH channels suffer from interference. It is seen that for a packet failure rate lower than 6.66 % (i.e. 5 out of 75), the FH system is unable to offer the required performance on its clear channels alone. Consequently, a high signal power is required in order to receive some packets correctly on the hit channels as well, resulting in a very low operating range. The range achieved below this threshold is dependent upon the level of interference observed at the receiver, however, once the performance requirement is relaxed and the packet failure rate can easily be achieved on clear channels only, the signal power required drops considerably. This results in a marked increase in operating range and since the performance is now determined only by the signal-to-noise ratio, it is independent of the level of interference power. In contrast, the DS system suffers greatly from a high level of in-band interference and a high signal power is necessary to achieve the required performance. Furthermore, relaxing the packet failure rate requirement has a minimal effect on the range offered, since when the level of interference is greater than the protection offered by the jamming margin of the DS system, the despreading process offers no advantage. As the interference power is reduced, by increasing the interferer-receiver separation, the performance of the DS system gradually improves, but is still considerably less than that offered by the FH system.

The operating range of the two systems of various levels of performance is shown in Figure 2. A 1% packet failure rate has been defined as the reference level of performance. By accepting an increase in the packet failure rate to 8%, the throughput reduces to 85.7 % of that possible at 1% PFR. Similarly at 15% PFR, the throughput is reduced to 71.4 % of the datum transmission rate. In order to define these throughputs at various packet failure rates the simplest assumption as to the nature of the MAC has been made: that every failed packet can be successfully retransmitted in a single attempt. Whilst this is a gross simplification, it allows comparison of system performance at the lowest level.

At a 1% packet failure rate it is seen that as the level of interference power increases, the signal power required to maintain the given performance rapidly increases, resulting in a dramatically reduced range for both the DS and FH systems. Given that the DS system has the advantage of reducing the level of interference power through the despreading process, it offers superior performance to FH. However by reducing the system throughput, the FH system offers a significant advantage by utilising the large number of clear channels and accepting that any packets transmitted on hit channels will inevitably be lost. Thus at an 8% packet failure rate, with the interferer 10m away, the FH system is able to operate at more than twice the range of the DS system. This improved range is at the cost of operating at 85% of the throughput of the DS system. In contrast, in the presence of narrowband interference, the DS system is unable to offer such a trade-off between operating range and throughput. As expected from Figure 1, reducing the packet failure requirement has a minimal effect in the signal power required to achieve that level of performance, hence only a minimal increase in range is achieved.

Conclusion

This paper has presented an analysis of the susceptibility to interference of Direct Sequence and Frequency Hopping spread spectrum systems. The nature of the interference has been assumed as being white noise-like and wholly in-band of the message signal. Whilst this is a simplification, it has allowed comparison of the two systems on a like-for-like basis.

It has been demonstrated that in the presence of high levels of interference which exceed the protection offered by the jamming margin, the performance of an ISM-band direct sequence system suffers greatly. A high signal power is required in order to achieve a reasonable packet failure rate, hence operation is limited to a low range. If the system performance requirement is too high and data must be transmitted on hit channels, a frequency hopped system is inferior since it is unable to reduce the level of interference power at the demodulator, as DS can. However, the advantage of employing frequency hopping in the presence of narrowband interference is that in general many clear channels exist. Thus, whilst a reduction in throughput arises, a high level of performance is achieved at signal powers dictated only by the receiver design, thereby offering significantly greater range than the DS system.

It should be made clear that the actual performance of the two schemes would be highly dependent upon the nature of the MAC layer, which would most likely be different for each system. This analysis has only compared the two systems on the basis of uncoded error rates appearing at the physical layer. Furthermore, it should be emphasised that which spread spectrum approach provides the best performance is dependent upon the precise nature of the interference: if the interference is wide band and hits many FH channels, its performance would suffer. However, in the case of the ISM bands where emissions from microwave ovens slew through the frequency band and appear as narrowband interference over the period of a single hop, it is proposed that frequency hopping offers the most robust solution.

Acknowledgement

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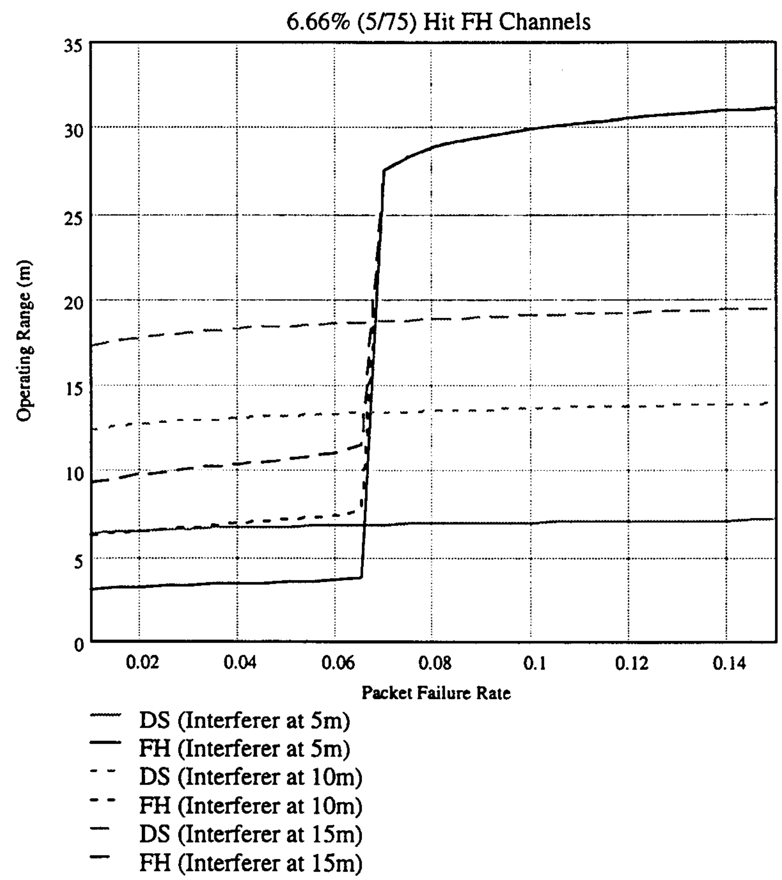

Figure 1. Performance versus Packet Failure Rate

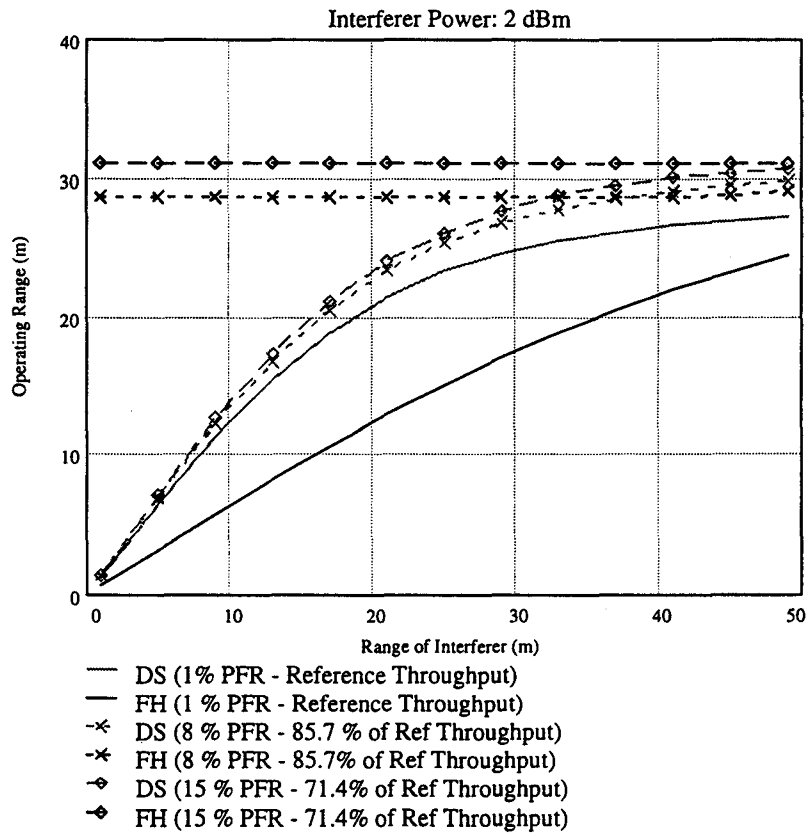

Figure 2. System performance in varying levels of interference