Performance Comparison Of Frequency Hopping And Direct Sequence Spread Spectrum Systems In The 2.4 GHz Range

Zoran Spasojevic, John Burns

Aegis Systems Ltd.

zoran.spasojevic@aegis-systems.co.uk , john.burns@aegis-systems.co.uk

ABSTRACT

The FHSS and DSSS technologies are described as well as different types of spread coding. DSSS systems can provide higher access data rates (up to 11Mbit/s) than FHSS systems (up to 3Mbit/s). More FHSS systems can operate simultaneously in the same area than DSSS systems. DSSS systems have higher interference susceptibility tolerance levels. However, if there is a strong broadband interferer in the operational spectrum, FHSS systems will suffer less due to frequency hopping. Assuming equal transmit powers, DSSS systems have lower power spectral density due to wider operating spectrum. Monte Carlo analysis results show that DSSS systems are more likely to cause interference than FHSS systems. The worst case interference levels are higher when the interferer is FHSS system. It was shown that this case has a very low probability of occurring.

I. INTRODUCTION

This report analyses the two main spread spectrum (SS) technologies used by wireless devices in the 2.4 GHz Industrial Scientific and Medical (ISM) band. Currently, the main SS application is radio local area networks (RLANs), however initiatives such as Bluetooth and various "home networking" technologies may in the next few years lead to many millions of SS devices being deployed in the band. The 2.4 GHz band is heavily used by high power devices such as commercial and domestic microwave ovens and outside broadcast television, resulting in a particularly severe interference environment. This report compares the technical characteristics of FHSS and DSSS systems. Monte Carlo modelling is then performed to simulate interference between large numbers of FHSS and DSSS systems. Conclusions of the study are drawn from the results of the modelling and from the technical comparison.

II. SPREAD SPECTRUM TECHNOLOGY

Most current 2.4 GHz SS systems are compliant with the IEEE 802.11 standard [1] and in Europe must comply with ETS 300 328 [2]. These standards cater for both FHSS and DSSS systems.

A. FHSS

In FHSS, the transmitter moves around a nominal centre frequency in a specific "hopping sequence". This is accomplished using a pseudo random "spreading code" to control a frequency agile local oscillator. A replica of the spreading code is applied at the receiver to recover the wanted information signal. Other FHSS transmissions with different hopping sequences are rejected by the narrow band IF filter, along with any wide band signal or noise content. In IEEE 802.11 FHSS systems hopping typically takes place over 79 channels, at centre frequencies 2402.0–2480.0 MHz with 1MHz spacing. A manufacturer has the option not to use certain frequencies if needed, for example to avoid known sources of interference. The standard allows up to 78 hop sequences, which are defined as 3 sets of 26 orthogonal sequences) with the minimum frequency separation between sequential hops being 6 MHz. Figure 1 illustrates frequency hopping concept with a frequency Vs. time chart.

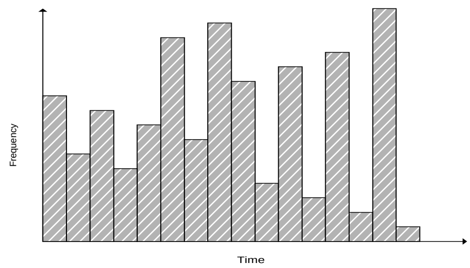

Figure 1. Illustration of frequency hopping concept.

The term orthogonal implies that there will not be co-channel or adjacent channel frequency collisions between different sequences in the same set. Maximum access data rate that a FHSS link can currently achieve is 3 Mbit/s (using 8FSK modulation). In general, frequency hopping systems can utilise fast frequency hopping (i.e. hopping rate greater than access data rate) or slow frequency hopping (i.e. hopping rate equal or smaller than access data rate). IEEE 802.11 compliant FHSS systems must hop at the minimum rate specified by the regulatory bodies of the intended country. For e.g., a minimum hop rate of 2.5 hops per second is specified for the United States.

B. DSSS

DSSS systems use a spreading signal that comprises a pseudo random sequence of positive and negative pulses at a very high repetition rate [3]. The spreading signal has a much higher bandwidth than the wanted information signal. The baseband signal is multiplied by the spreading signal, then up-converted to 2.4 GHz. At the receiver, the spread signal is recovered by applying a "de-spreading" code that is identical to the spreading signal applied at the transmitter. The spreading codes have good auto correlation properties and the cross-correlation between two different spreading code sequences is low. These two properties of spreading codes are very important for any DSSS system, since they ensure that only wanted signal is recovered by the de-spreading mechanism. Other signals (that are multiplexed with a different spreading code) and interfering signals will normally blend into AWGN signals after de-spreading. The bandwidth ratio of the spread signal to the baseband signal is referred to as the "processing gain". In general, the higher the processing gain, the more resilient the DSSS system will be.

IEEE 802.11 compliant DSSS systems use an 11 bit Barker spreading code which provides a processing gain of 10.4 dB. The current standard provides for a maximum bit rate of 2 Mbit/s, using QPSK modulation. However, work has recently been completed on two 11 Mbit/s variants, using Cyclic Code Keying (CCK) and Orthogonal Frequency Division Multiplex (OFDM)**.** The RF bandwidth in both cases is 22 MHz.

C. Coding

There are three main aspects that need to be considered when choosing the appropriate spreading code in DSSS systems. These are chip rate, correlation properties and the implementation cost of code processing.

Chip rate determines the spread RF bandwidth and the processing gain. As shown in equations 1 and 2 below, for a 22 MHz DSSS system with data rates up to 2Mbit/s, chip rate is limited to 11Mchip/s. Processing gain is equal to:

$$10.4\text{dB}=10*\log(BW/BR)=10\log(C/S) \qquad (1)$$

where:

BW is the system bandwidth of 22 MHz
BR is the bit rate assumed to be 2Mbit/s
C/S is the ratio of chip rate and symbol rate, where the symbol rate is equal to 1 Msymbol/s.

It is important to stress that the processing gain [4] in equation 1 is defined differently than in many textbooks, which define processing gain as the ratio of chips per data bit (or ratio of spread rate to bit rate). However IEEE 802.11 regulations use the FCC rule that defines processing gain as the ratio between spread bandwidth per bit rate (or in the case of IEEE 802.11 compliant DSSS system also ratio of chip rate and symbol rate). These two definitions can lead to different results as indeed happens in the case of IEEE 802.11 compliant DSSS RLAN. If the textbook rule is used then the processing gain will be 5.5 dB as opposed to the calculated 10.4 dB. Chip rate is hence in this case equal to 11Mchips/s.

Other DSSS systems may utilise faster chip rates (and different types of coding sequence) but as the processing capabilities of a DSSS system are increased, the synchronisation of spreading codes becomes more challenging and the complexity of the system is increased.

Autocorrelation is achieved by correlating a coding sequence against the time shifted version of itself. A spreading code should have good autocorrelation to make synchronisation easier. A good autocorrelation function is one which has one main peak and a minimal number (ideally none) of secondary peaks. Cross-correlation is achieved by correlating differenting coding sequences. For CDMA purposes, it is important that the degree of correlation between different codes is minimised (ideally to have zero cross-correlation). Longer pseudorandom code sequences such as Gold, Kasami and m-ary code sequences can provide excellent autocorrelation properties and meet cross-correlation requirements. These sequences are often used as a scrambling sequences in CDMA systems. Others types like Walsh-Hadamard codes provide orthogonal sequences which means that if you take any two different sequences and cross-correlate them (with time shift equal to zero) the result would be zero. Obviously, correlation of any digital code sequence with a non-shifted version of itself gives 1. The disadvantage of these sequences is that they assume no time shift. Orthogonality between sequences does not hold when there is a time shift between sequences (due to multipath or asynchronous operation). Auto-correlation and cross-correlation requirements would not be satisfied anymore. Orthogonal sequences are normally used in CDMA operation for channelisation purposes whilst the above mentioned long PN sequences are used for scrambling purposes (thus providing a composite signal that satisfies required auto-correlation and cross-correlation properties).

IEEE 802.11 systems will not allow for CDMA due to their low processing gain. Therefore long PN sequences that require more expensive implementation costs than the shorter Barker codes are no longer necessary. An attribute of the Barker sequence is a very good multipath resilience. Longer Barker sequences (13,15 and 16 bit) have not been chosen because it was desired that only minimum necessary bandwidth is utilised. The cost of implementing the code sequence also increases with the length and complexity of the coding process.

III. FHSS VS DSSS PERFORMANCE COMPARISON

A. Multiple Access Operation

As mentioned in previous sections, multiple access operation on the same channel is not possible in IEEE 802.11 DSSS systems. From the processing gain of 10.4dB, a typical minimum carrier-to-interference ratio of approximately 3dB for QPSK modulation and 1dB for BPSK modulation can be calculated. Therefore, co-located co-channel DSSS systems will mutually interfere. This means that a maximum three DSSS systems with non-overlapping channels (up to 5 with overlapping channels) can be co-located with each occupying a different 22 MHz portion of the frequency range.

Theoretically FHSS caters for as many as 26 co-located networks sharing the band if minimal interference is to be obtained since at any time there should be 26 orthogonal hopping sequences. However, different RLAN FHSS systems are not necessarily synchronised and if this is the case then orthogonality between hopping sequences is compromised, reducing the number of possible co-located systems. In practice, the upper practical limit of uncoordinated co-located FHSS RLAN systems is approximately 15 because it has been experimentally proven that “hopping” sequences from the same set collide in average 3 times (maximum 5 times) over hopping pattern cycle.

B. Interference Susceptibility

Since FHSS systems change frequency by at least 6 MHz between hops and can operate over the entire ISM band, they can tolerate a significant amount of in-band interference providing that it affects only part of the spectrum. In general, the speed and capacity of an FHSS system degrades in proportion to the number of lost channels, e.g., if 30% of available frequencies are unusable due to interference, an FHSS system will still operate at 70% of its capacity.

IEEE802.11 DSSS systems occupy a nominal 22 MHz bandwidth and a broadband interference source (such as microwave ovens) or a large number of in-band narrowband interference sources can affect the QoS of the entire DSSS channel. On the other hand, DSSS systems with 2Mbit/s data throughput can tolerate interference up to a level that is only 3 dB smaller than the wanted signal, compared to 19 dB for a 2 Mbit/s FHSS.

As a consequence of the better interference tolerance of DSSS systems, it is theoretically possible to operate the groups of 3 possible DSSS systems much closer together than the groups of 15 FHSS systems. This may have an impact on the total number of RLAN systems per unit area.

In conclusion, FHSS has an advantage providing that a large chunk of its frequencies are not affected. Small levels of broadband interference are often well tolerated by high interference limits of DSSS system but not by FHSS systems.

A narrowband (<=1MHz) interference source will have less impact on DHSS system since it will only affect a small part of its channel bandwidth whilst it would very probably disable the operation of FHSS system on one of its hopping channels. Further on, if there are say 10 or so narrow band interferers, they may not significantly disrupt the operation of a DSSS system if the total interference power is at least 3 dB less than the wanted signal, but they might disable a significant number of FHSS channels.

C. Power Spectral Density

Assuming equal transmit powers being uniformly distributed across 22 MHz (in the DSSS case) and 1 MHz (in the FHSS case) range, the power spectral density will be 13.4 dBW/MHz lower for the DSSS systems than for FHSS systems. This will reduce the potential for interference from a DSSS system in any 1MHz frequency range. On the other hand, DSSS systems may interfere with more users because of their wider bandwidth. The frequency hopping of FHSS systems compensates for the higher power spectral density since the system will only operate a small percentage of its operating time at any 1 MHz frequency channel.

IV. MONTE CARLO ANALYSIS

A. Analysis Overview

The interference between different spread spectrum RLAN systems was analysed and modelled using a statistical Monte Carlo software tool. The modelling tool assumes a single victim receiver and multiple, randomly located interferers. Input parameters into the tool include radio and logistical parameters related to both the victim and the interfering systems. Interference into the victim from as many as three different types of interfering systems is calculated a pre-specified number of times. The outputs of the tool are a probability density function (PDF) and a cumulative density function (CDF) distributions for the calculated interference levels. Depending on the environment, the tool assumes either multislope or Okumura-Hata propagation model in calculating interference levels. The multislope model assumes free space propagation up to distances of 1 km and a fourth power law beyond. A free space model can in some cases be appropriate when outdoor systems are analysed, particularly in rural environments. In the analysis, the urban mode of the Okumura-Hata propagation model for analysing the interference to and from the indoor RLAN systems has been used.

For FHSS, the CDF represents the probability of a given level of interference being exceeded for a certain percentage of time. The CDF is thus the number of affected hopping channels at any instant in time. For DSSS, the CDF distribution represents the probability of a given interference level being exceeded when the interferers are randomly located in a pre-defined area.

B. Modelling Parameters

Interference scenarios were modelled for both outdoor and indoor systems. Radio parameters (based on commercial IEEE 802.11 equipment) are illustrated in the following Table.

Table 1. Radio parameters used in modelling

Parameter:	**FHSS**	**DSSS**
Total EIRP	-10dBW/MHz	-20dBW/MHz
Duty cycle	1.27% (on each specific hop frequency)	100%
Maximum data rate	3Mbit/s	11Mbit/s
Interference limits	-125dBW/MHz	-121dBW/MHz
Receiver bandwidth	1 MHz	22MHz
Antenna (indoor)	Omnidirectional, 2dBi	Omnidirectional 2dBi
Antenna (outdoor)	Directional, 10 dBi	Directional, 10 dBi

The most important logistical parameters to model are interferer geographic density, maximum distance between possible interferers and victim, and antenna heights. Geographic density was based on current and predicted demographic data and varies from area to area. In the UK, it varies from a maximum of 800 per square km in the City of London to a handful per square km in rural areas. Modelling concentrated on urban environments with densities between 20 and 800 indoor transmitters per km^2 and between 0.4 and 2 outdoor transmitters per km^2. The assumed maximum distance between interferer and victim for a urban environment was 6 km. Typical antenna heights were 5 metres (indoor) and 30m (outdoor).

V. MODELLING RESULTS

Indoor and outdoor RLAN densities of 100 and 1 per km^2 respectively are used for illustration purposes. The operating frequency is taken to be 2422 MHz (ie lowest DSSS carrier frequency).

A. Interference From Outdoor RLAN Systems

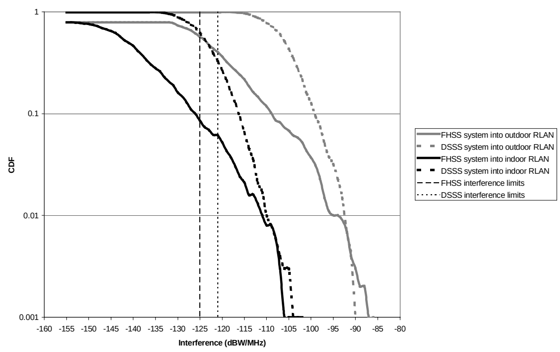

Figure 2. Interference CDF plots when the interference is caused by outdoor RLANs

From Figure 2 it is obvious that if the outdoor interferer density reaches the suggested levels, the interference between two outdoor systems (both DSSS and FHSS) will be very high. This is also true for the case of intra-system interference when there is a similar density of co-channel outdoor RLAN transceivers deployed in one system. Outdoor RLAN network planners should take this into consideration in planning future system deployment.

It can be also be seen that FHSS outdoor systems may cause higher interference peak levels. Although the specifications suggest that both systems have the same maximum transmit power (100mW), the transmit power in the FHSS system is spread over a 1MHz channel whereas for DHSS the channel bandwidth is 22 MHz. However, the probability that the higher peak interference levels are obtained is very small (approximately 0.1%).

The interference CDF curve for the case when the DSSS RLAN is the interferer is much steeper than in FHSS case. The probability that a DSSS RLAN system will cause interference into another RLAN system is significantly higher (except for the peak interference levels as explained above) than if the interferer is FHSS system, since the DSSS interference is present in the affected channel continuously.

Finally, it can be deduced that a FHSS system is more resilient to co-channel interference than a DSSS system. The carrier frequency of an FHSS system changes by at least 6MHz every hop so if interference affects a large portion of frequencies (say between 15 and 20 MHz) in the range the performance (speed and capacity) will be degraded by a similar amount. However, if the same portion of frequencies in a DSSS system is exposed to significant interference levels, performance of the system can be seriously affected. On the other hand, since DSSS systems can tolerate lower carrier-to-noise levels than FHSS and if the interferer has a narrow band relative to the spreading signal, its effect will be reduced by the ratio between two bandwidths.

B. Interference From Indoor RLAN Systems

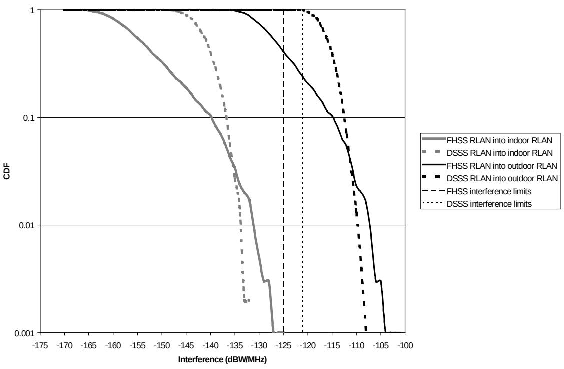

Figure 3. Interference CDF plots when the interference is caused by indoor RLANs

Interference levels from indoor systems are much smaller than in the outdoor case since indoor RLAN systems in different buildings (and different floors of the same building) are analysed. These systems are normally shielded by building structures, their transceiver antennas are at lower heights and the propagation losses are greater in this case since the penetration of these systems is most likely to be in urban and dense urban environments such as main shopping areas, industrial and residential estates. Also, indoor RLANs are mostly planned in such a way to produce smaller coverage cells than in the outdoor system case. Building penetration losses used in modelling are specified in Table 1.

Indoor RLAN systems co-located in the same room (or in the same building area) are not modelled since it is unrealistic that such systems would be deployed. However if such systems are deployed, the inter-system interference could have serious effects on operation of both systems, since they would most probably be deployed at a relatively small mutual separation and most probably without any significant mutual shielding.

Indoor DSSS RLAN system appear to have a higher probability of causing interference at an observed carrier frequency than an indoor FHSS RLAN system. Also, indoor FHSS RLAN system is more resilient to interference at an observed carrier frequency than an indoor DSSS RLAN system.

VI. CONCLUSION

On the basis of currently available technology and recent standards developments, and as a result of the analysis explained in this report it is likely that FHSS systems will provide greater resilience to interference and will therefore be preferable for applications such as RLANs where it is necessary to deliver a specific grade of service. Whilst future developments such as the introduction of DSSS systems with higher chip rates which would enable operation of true CDMA cannot be ruled out, these may be unsuitable for operation in the presence of very high power interference sources such as outside broadcast TV.

FHSS systems are likely to produce higher peak interference due to larger power spectral density, but the probability of interference occurring is generally larger when the interferer is DSSS system. Also, widespread deployment of DSSS systems could cause problems for FHSS systems since the whole band would suffer continuous interference from DSSS signals.

DSSS is likely to provide greater throughput per system for the foreseeable future, by virtue of the wider RF channels, however this benefit may be compromised to some extent where multiple DSSS systems are co-located. This may for example lead to problems if more than three outdoor DSSS systems are operated in the same geographic region, where the transmission path between interferer and victim may be substantially line of sight.

REFERENCES

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