

Frequency Hopping Spread Spectrum (FHSS) vs. Direct Sequence Spread Spectrum (DSSS) in Broadband Wireless Access (BWA) and Wireless LAN (WLAN)

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Scope

In 1997 IEEE defined the 802.11 Wireless LAN (WLAN) standard, intended to allow wireless connection of workstations to their “base” LAN. The original standard targeted the case in which both the workstation and the LAN were owned by the same entity, providing in fact a wireless extension to an existing, wired LAN.

While this WLAN application represents a growing niche in the market, the technology on which it is based started to be used also for a new application, that of providing Broadband Wireless Access (BWA) to public networks. We are still connecting workstations to “base” LAN, but this time the “base” LAN is owned by a service provider (ISP, ITSP, ILEC, CLEC), while the workstation is owned by a subscriber.

This white paper explains the principles of the FHSS and DSSS radio technologies used in WLAN and BWA applications as well as the advantages and disadvantages of each one of them.

Executive Summary

WLANs may be implemented using optical or radio technologies for the transmission of the signals through the air, and both are defined in the IEEE 802.11 standard, ratified on June 26, 1997. While the original standard defined rates of 1 Mbps and 2 Mbps only, later enhancements, added the rates of 5.5 Mbps and 11 Mbps, too.

The radio technology on which WLANs are based is known as Spread Spectrum modulation and has its origins in the military. Among the advantages of Spread Spectrum technologies, one can mention the inherent transmission security, resistance to interference from other radio sources, redundancy, resistance to multipath and fading effects, etc. As a result, Spread Spectrum systems can coexist with other radio systems, without being disturbed by their presence and without disturbing their activity.

The immediate effect of this elegant behavior is that Spread Spectrum systems may be operated without the need for license, and that made the Spread Spectrum modulation to be the chosen technology for license-free WLAN and BWA operation.

However, as mentioned above, spread spectrum technologies have many other advantages, making them an excellent option for the operation of systems in licensed bands, too.

There are basically two types of Spread Spectrum modulation techniques: Frequency Hopping (FHSS) and Direct Sequence (DSSS).

This white paper presents these two “competing” technologies comparing their performance relative to a few parameters of crucial importance in communications systems:

- possibility to collocate systems
- noise and interference immunity
- data transfer capacity (throughput)
- operation in environments generating radio reflections
- security
- resistance to interference generated by Bluetooth / IEEE 802.15 WPAN (Wireless Personal Area Networks).

The conclusion will be - as expected - that there is no “good” technology and “bad” technology, but that there are applications where FHSS performs better than DSSS, and obviously there are applications where the opposite is true.

This white paper explores the two technologies for the purpose of identifying these applications.

And for those interested just in the conclusions, here they are:

DSSS has the advantage of providing higher capacities than FHSS, but it is a very sensitive technology, influenced by many environment factors (mainly reflections). The best way to minimize such influences is to use the technology in either (i) point to multipoint, short distances applications or (ii) long distance applications, but point to point topologies.

In both cases the systems can take advantage of the high capacity offered by DSSS technology, without paying the price of being disturbed by the effect of reflections.

As so, typical DSSS applications include indoor wireless LAN in offices (i), building to building links (ii), Point of Presence (PoP) to Base Station links (in cellular deployment systems) (ii), etc.

On the other hand, **FHSS** is a very robust technology, with little influence from noises, reflections, other radio stations or other environment factors. In addition, the number of simultaneously active systems in the same geographic area (collocated systems) is significantly higher than the equivalent number for DSSS systems.

All these features make the FHSS technology the one to be selected for installations designed to cover big areas where a big number of collocated systems is required and where the use of directional antennas in order to minimize environment factors influence is impossible.

Typical applications for FHSS include cellular deployments for fixed Broadband Wireless Access (BWA), where the use of DSSS is virtually impossible because of its limitations.

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A.- Basic principles

Spread Spectrum

Spread Spectrum modulation techniques are defined as being those techniques in which:

- The bandwidth of the transmitted signal is much greater than the bandwidth of the original message, and
- The bandwidth of the transmitted signal is determined by the message to be transmitted and by an additional signal known as the Spreading Code.

Two main Spread Spectrum modulation techniques are defined: Frequency Hopping Spread Spectrum (FHSS) and Direct Sequence Spread Spectrum (DSSS). By transmitting the message energy over a bandwidth much wider than the minimum required, Spread Spectrum modulation techniques present two major advantages: low power density and redundancy.

Low power density relates to the fact that the transmitted energy is spread over a wide band, and therefore, the amount of energy per specific frequency is very low. The effect of the low power density of the transmitted signal is that such a signal will not disturb (interfere with) the activity of other systems' receivers in the same area and that such a signal can not be detected by intruders, providing a high level of intrinsic security.

Redundancy relates to the fact that the message is (or may be) present on different frequencies from where it may be recovered in case of errors. The effect of redundancy is that Spread Spectrum systems present high resistance to noises and interference, being able to recover their messages even if noises are present on the medium.

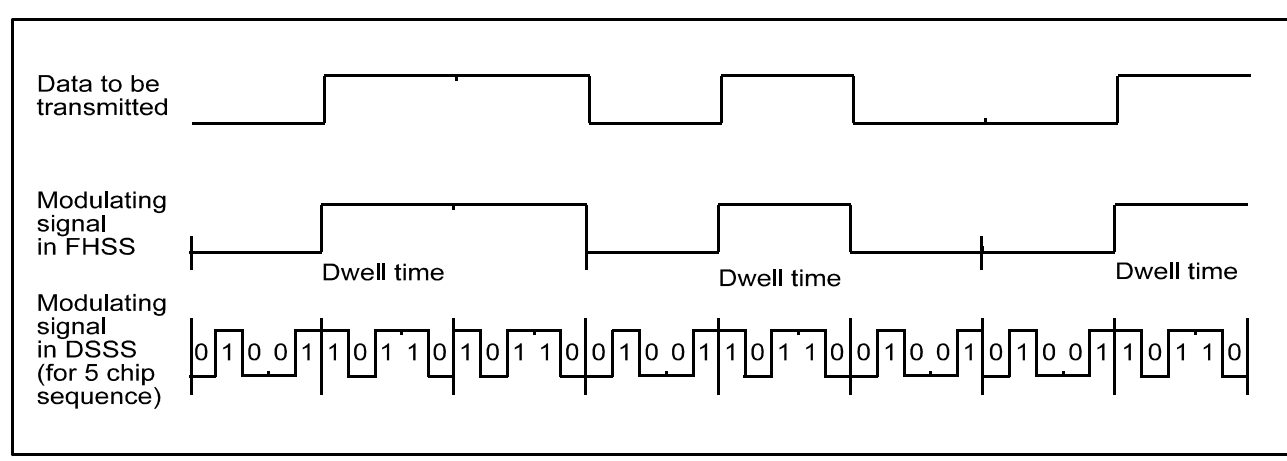


Figure 1 - Signals used to modulate the carrier in FHSS and DSSS (Dwell time in FHSS is represented as 3 x data bit duration. Spreading sequence in DSSS is represented as being 5 chip long)

Notes:

- 1.- FHSS: The frequency of the carrier has a different value for each dwell time.
- 2.- DSSS: The frequency of the carrier has a constant, fixed value for each system.

WLAN and WBA applications in the unlicensed spectrum use the frequency band known as "2.4 GHz" (ranging from 2.4 GHz to 2.4835 GHz, same as the Industrial, Scientific and Medical - ISM band). The operation in this band is defined by IEEE 802.11.

For licensed spectrum operation, most applications use the so called “sub 11 GHz bands” including frequencies such as 2.5 GHz, 2.6 GHz, 3.5 GHz, 3.6 GHz, 3.8 GHz, etc.

Spread Spectrum modulation techniques are composed of two consecutive modulation processes executed on the carrier signal (Fig. 1):

- Process 1 - executed by the spreading code (= the spreading process). It is this spreading process that generates the wide bandwidth of the transmitted signal.
- Process 2 - executed by the message to be transmitted.

FHSS

- Process 1 - Spreading code modulation

The frequency of the carrier is periodically modified (hopped) following a specific sequence of frequencies.

In FHSS systems, the **spreading code** is this list of frequencies to be used for the carrier signal, a.k.a. the “hopping sequence”

The amount of time spent on each hop is known as dwell time and is typically in the range of 100 ms.

- Process 2 - Message modulation

The message modulates the (hopping) carrier (FSK), thus generating a narrow band signal for the duration of each dwell, but generating a wide band signal, if the process is regarded over periods of time in the range of seconds.

- Redundancy is achieved through the possibility to execute re-transmissions on different carrier frequencies (hops).

DSSS

- Process 1 - Spreading code modulation

For the duration of every message bit, the carrier is modulated (PSK) following a specific sequence of bits (known as chips). The process is known as “chipping” and results in the substitution of every message bit by (same) sequence of chips.

In DSSS systems, the **spreading code** is the chip sequence used to represent message bits.

- Process 2 - Message modulation

For message bits “0”, the sequence of chips used to represent the bit remains as dictated by process 1 above. For message bits “1”, the sequence of chips dictated by process 1 above, is inverted. In this way message bits “0” and “1” are represented (over the air) by different chip sequences (one being the inverted version of the other one).

- Redundancy is achieved by the presence of the message bit on each chip of the spreading code. Even if some of the chips of the spreading code are affected by noise, the receiver may recognize the sequence and take a correct decision regarding the received message bit.

B.- IEEE 802.11

As mentioned above, IEEE 802.11 is the standard defining WLAN operation. As so, it deals with the Physical (PHY) and Media Access Control (MAC) layers of the OSI seven layers model.

FHSS and DSSS parameters are defined in the PHY sections of the standard

List of IEEE 802.11 task groups (as of December 2001):

- IEEE 802.11 - FHSS and DSSS basic operation (MAC and PHY) at 1Mbps and 2 Mbps, in the 2.4 GHz unlicensed band.
- IEEE 802.11.a - OFDM operation (PHY) at 6 - 54 Mbps, in the 5 GHz band
- IEEE 802.11.b - DSSS operation (PHY) at 5.5 and 11 Mbps, in the 2.4 GHz band
- IEEE 802.11.c - Bridging 802.11 frames (supplement to IEEE 802.1.d)
- IEEE 802.11.d - Extensions to operate in additional regulatory domains (country specific bands)
- IEEE 802.11.e - MAC enhancements for QoS (EDCF - Enhanced DCF; HCF - Hybrid Coordination Function)
- IEEE 802.11.f - Recommended practice for Inter Access Point Protocol (IAPP)
- IEEE 802.11.g - Higher rate extensions to 802.11.b (at least 20 Mbps)
- IEEE 802.11.h - Spectrum managed 802.11.a (SMa) (DCS - Dynamic Channel Selection; TPC - Transmit Power Control)
- IEEE 802.11.i - MAC enhancements for enhanced security

FHSS main parameters

FHSS is defined (in IEEE 802.11) in the 2.4 GHz band as operating over 79 frequencies ranging from 2.402 GHz to 2.480 GHz (country specific bands have different frequencies, defined in IEEE 802.11 and IEEE 802.11.d).

Each of the frequencies is GFSK modulated, with a channel width of 1 MHz.

The rates defined are 1 Mbps and 2 Mbps (there are products in the market operating at 3 Mbps, too)

DSSS main parameters

DSSS is defined (in IEEE 802.11) in the 2.4 GHz band as operating on one of 14 possible carriers (country specific bands have different number of frequencies, defined in IEEE 802.11 and IEEE 802.11.d).

The selected carrier (channel) is PSK modulated with a channel width of 22 MHz.

The rates defined in IEEE 802.11 are 1 Mbps and 2 Mbps.

IEEE 802.11.b adds to DSSS the rates of 5.5 Mbps and 11 Mbps (in the 2.4 GHz band), while keeping the channel width at 22 MHz.

C.- Systems Behavior

The following issues will be studied in parallel for FHSS and DSSS systems:

- 1.- Systems Collocation
- 2.- Noise and Interference Immunity
- 3.- The Near / Far problem
- 4.- Throughput
- 5.- Multipath Immunity
- 6.- Time and frequency diversity
- 7.- Security
- 8.- Bluetooth interference

1.- Systems Collocation

The issue: *How many independent systems may operate simultaneously without interference?*

In **DSSS** systems, collocation could be based on the use of different spreading codes (sequences) for each active system (CDMA = Code Division Multiple Access). On condition that the sequences used are highly distinguishable one from the other one (property known as orthogonality) each receiver will be able to “read” only the information dedicated to it (receiver and transmitter use same spreading code). CDMA could indeed be the solution, but orthogonal pseudo-random sequences are needed. The number of orthogonal pseudo-random sequences is limited and it is a function of the sequence length [number of chips (bits) in the sequence].

(The following table is taken from “Modern Communications and Spread Spectrum” by G.R. Cooper and C. D. McGillan)

Length of sequence (in chips)	Number of available sequences	Number of possible collocated systems
15	2	2
31	6	6
63	6	6
255	16	16
1,023	60	60

For the collocation of 16 systems, 255 chip (bit) long sequences should be used. Every message bit should be represented by 255 bits! If message rate is 1 Mbps (minimum required in LANs), the rate of the transmitted signal (over the air) would be 255 Mbps ! Expensive!

Actual (IEEE 802.11 and 802.11.a based) DSSS systems use 11 bit long spreading sequences making the use of CDMA impossible. System collocation is therefore based on the fixed allocation of bandwidth to each system (same as in narrow band systems).

For the transmission of 11 Mchips per second (Msymbols per sec), IEEE 802.11 needs a contiguous band of 22 MHz, and defines the need for a minimum distance of 30 MHz between the carrier frequencies of collocated DSSS systems.

As the total available bandwidth in the ISM band is 83.5MHz (2.4GHz - 2.4835GHz) and as the distance between carriers has to be 30 MHz, only 3 DSSS systems may be collocated, without interference.

If more than 3 systems are collocated, their contiguous 22 MHz channels will overlap, forcing their users to share the channels. The actual behavior and the amount of actual interference is a function of the overlapping size and signal strength.

For **FHSS** systems, IEEE 802.11 defines 79 different hops for the carrier frequency. Using these 79 frequencies, IEEE 802.11 defines 78 hopping sequences (each with 79 hops) grouped in three sets of 26 sequences each. Sequences from same set encounter minimum collisions and therefore may be allocated to collocated systems. Theoretically, 26 FHSS systems may be collocated, but collisions will still occur in significant amounts. To lower the amount of collisions to acceptable levels, the actual number of FHSS collocated systems should be around 15.

All the above is correct for the case in which the FHSS collocated systems operate independently, without any synchronization among their hopping sequences.

If synchronization is allowed, 79 systems could be collocated (theoretically), each one of them using at any moment in time, one of the 79 available frequencies. However, this would require expensive filters in the radio circuitry. Actual products require about 6 MHz separation allowing the collocation of about 12 systems, without any collision! While such synchronization is not always allowed in the unlicensed band of 2.4 GHz, it is common practice in the licensed bands.

The possibility of having collocated systems without collisions, has a tremendous impact on the aggregate capacity / throughput of the installation as well as its efficiency in terms of bps per Hz (see "Throughput" section, later in this paper).

A prime conclusion: For installations requiring big coverage and multiple collocated cells, it would be much easier to use FHSS. DSSS could be used, too, but then, mechanically collocated cells (antennas installed on same pole) should be made non overlapping cells at the radio level, ... through the use of directional antennas... But directional antennas means limited coverage, ... requiring more systems to be installed, ... which are difficult to design because of the collocation issue...

This severe limitation of DSSS is in effect for the 2Mbps flavor of DSSS as well as for the 11Mbps one.

2.- Noise and Interference Immunity

The issue: Capability to operate when other radio signals are present in the same band.

FHSS systems operate with SNR (Signal to Noise Ratio) of about 18 dB.

DSSS systems, because of the more efficient modulation technique used (PSK), can operate with SNR as low as 12 dB.

2.1.- All band interference

As DSSS systems can operate with lower SNR, for a given level of all band interference (interference covering the whole spectrum used by the radio), for same level of transmitted energy, DSSS systems can operate over longer distances than FHSS systems.

Let's remember however that the "whole spectrum used by the radio" is 83.5 MHz in FHSS (the whole ISM band) while for DSSS it is only 22 MHz (one of the sub-bands). The chances of having an interference covering a range of 22 MHz are obviously greater than the chances of having the interference covering 83.5 MHz! A 22 MHz wide interference may totally block a DSSS system, while it will block only 33% of the hops in a FHSS system. A FHSS system will work in these conditions at 66% of its capacity, but it will work! A DSSS system would not!

2.2.- Narrow band interference

DSSS systems have to be able to receive the energy present in their "working band" which is 22 MHz. The filters included in the radio interface allow all the signals present in the working band to enter the device. A narrow band interference signal (interference present around one single frequency) is accepted by the receiver, and if enough energy is present on it, the interfering signal will totally block the receiver.

FHSS systems work with narrow band signals (located each time around a different carrier frequency) and therefore the filters included in the radio have a much narrower pass band. A narrow band interference signal present on a specific frequency, will block only one specific hop (or maybe a couple, if the interfering signal has a wider band). The FHSS receiver will not be able to operate at that specific hop, but, after hopping to a different frequency, the narrow filter will reject the interfering signal, and the hopper will execute reception without being disturbed... (In IEEE 802.11 the frequencies for consecutive hops are separated by at least 6 MHz in order to reduce to a minimum the chances of being disturbed by same interference on two consecutive hops).

3.- Near / Far problem

The issue: *The problems generated to a receiver by other active transmitters located in its proximity, are known as Near / Far problems.*

The interfering signals described above may be generated for example by a "foreign" radio transmitter located close to "my" receiver. The signals generated by the "foreign" transmitter, being received by "my" receiver at higher power levels, could blind it, making it unable to hear its partner. While the problem is critical in DSSS systems, if the receiver is FHSS, the worst case will be that the "foreign" transmitter will block SOME hops, forcing "my" FHSS system to work in less than optimum conditions, but allowing it to work !

4.- Throughput

The issue: *What amount of data is actually carried by the system (measured in bps).*

The RATE of a system is defined as the amount of data (per second) carried by a system WHEN IT IS ACTIVE. As most communications systems are not able to carry data 100% of the time, an additional parameter - the THROUGHPUT - is defined, as the AVERAGE amount of data (per second) carried by the system. The average is calculated over long periods of time. Obviously, the throughput of a system is lower than its rate.

In addition, when looking for the amount of data carried, the overhead introduced by the communication protocol should be considered, too.

(For an Ethernet network for example, the rate is 10 Mbps, but the throughput is 3 Mbps to 4 Mbps only! ... and some of these bits are the header of layer 2, some are the header of layer 3, 4, 5, 6, 7,

and only some of these bits (not ALL of them) are the “real” data bits, those bits generated by the application...)

4.1.- Single system throughput

DSSS systems transmit at rates of up to 11 Mbps; to do this they use a contiguous sub-band of 22 MHz. The efficiency of such a system is $11 \text{ Mbps} / 22 \text{ MHz} = 0.5 \text{ bits} / \text{Hertz}$.

FHSS systems (as of today) transmit at rates of up to 3 Mbps; to do this they use a channel of 1 MHz. The efficiency of such a system is $3 \text{ Mbps} / 1 \text{ MHz} = 3 \text{ bits} / \text{Hertz}$. As a result of the latest FCC decision (summer 2000) to allow FHSS operation in the 2.4 GHz band with 5MHz channels (instead of 1 MHz), FHSS systems operating at about 15 Mbps should be expected in the market in the future.

The above numbers represent the rates of the systems.

The throughput is about 7 Mbps for 11 Mbps DSSS, and about 2 Mbps for 3 Mbps FHSS.

4.2.- Aggregate throughput of collocated systems (Fig. 4)

Based on the IEEE 802.11 specifications, the maximum number of DSSS systems that can be collocated is 3. These 3 collocated systems provide an aggregate rate of $3 \times 11 \text{ Mbps} = 33 \text{ Mbps}$, or a net aggregate throughput of about $3 \times 7 \text{ Mbps} = 21 \text{ Mbps}$. Let’s note that because of the rigid allocation of sub-bands to systems, collisions between signals generated by collocated systems do not occur, and therefore the aggregate throughput is a linear function of the number of systems.

FHSS systems may be operated with synchronized or non-synchronized hopping sequences, based on the world region and on the allocated spectrum (unlicensed or licensed).

In the non-synchronized case, as the band is allocated in a dynamic way among the collocated systems (they use different hopping sequences which are not synchronized), collisions do occur, lowering the actual throughput.

The greater the number of collocated systems (APs), the greater the number of collisions. For small quantities of collocated APs, each additional AP brings in almost all its net throughput; the amount of collisions added to the system is not significant. When the number of APs reaches about 15, the amount of collisions generated by additional APs is so high that in total they lower the aggregate throughput.

In the synchronized case, collisions are totally eliminated, up to 12 systems can be collocated (see “Systems collocation” section in this paper), and the aggregate rate and throughput is a linear function of the number of collocated systems.

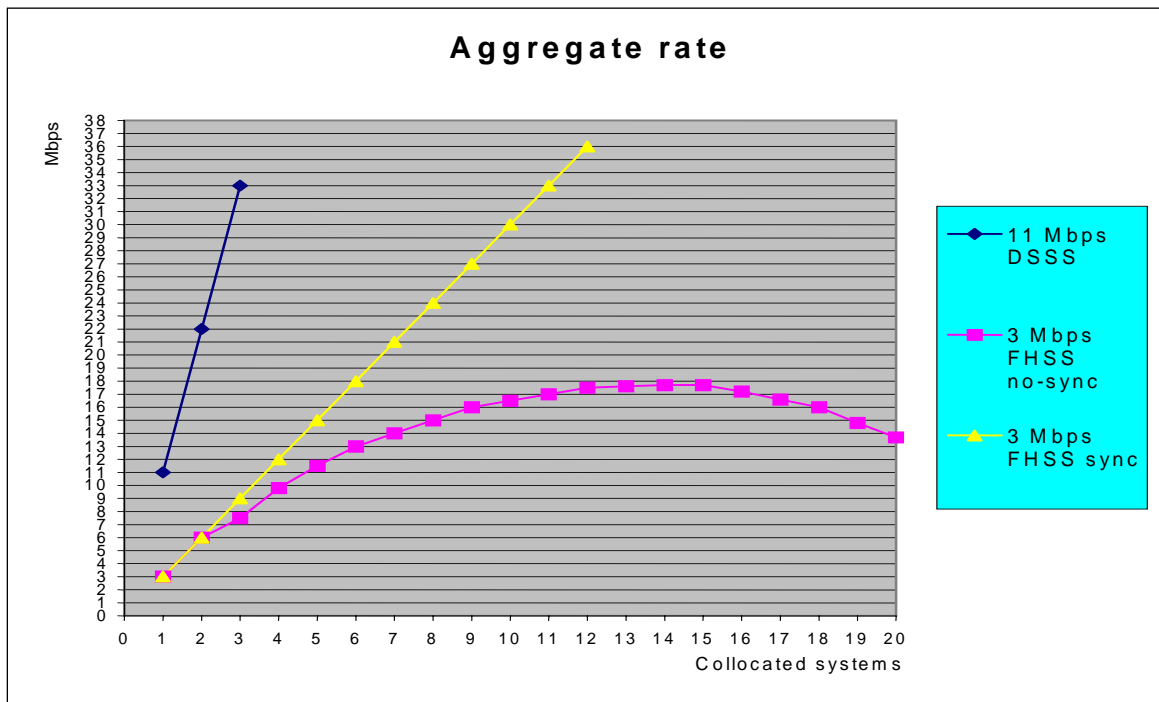


Fig.4 - Aggregate rate of collocated systems

Studying the graphs above, one can conclude that:

- DSSS systems provide a greater aggregate rate / throughput than non-synchronized FHSS systems. (DSSS systems are always separated in terms of frequencies and never collide; non-synchronized FHSS are not separated in terms of frequencies, collisions occur, and the resultant aggregate rate / throughput is lower)

- Synchronized FHSS systems never collide, and as a result, they provide more or less the same aggregate rate / throughput as DSSS systems. We should mention however, that even if the aggregate numbers are equivalent, the way these capacity is distributed among the users is different: DSSS has the advantage of providing independent users with rates of up to 11 Mbps, while FHSS provides a maximum of 3 Mbps per independent user.

So, if there is no way of synchronizing the APs (because the local radio regulations do not allow synchronization, or because the APs are geographically distributed, e.g. a WLAN in an office space), then, DSSS provides higher aggregate (and individual) rates / throughputs.

However, when synchronization is allowed and possible (e.g. a base station in a cellular deployment, where all the APs are located on same pole, and / or the system is operated in a licensed band), then FHSS would be recommended, as it provides slightly higher aggregate numbers.

5.- Multipath

The issue: Environments with reflective surfaces (such as buildings, office walls, etc.) generate multiple possible propagation paths between transmitter and receiver and therefore the receiver receives multiple copies of the original (transmitted) signal, shifted in time.

The effect of receiving multiple copies due to multipath will be analyzed separately in the time domain and in the frequency domain.

5.1.- Effect of multipath as seen in the time domain

The paths available for the transmitted signal to propagate through have different lengths and as a result, signal propagation time is different from one path to another and therefore the multiple copies (of the original signal) arriving at the receiver are shifted in time. [Remember the ghost (multiple) images in TVs? - it is the effect of multipath!]

In DSSS systems, the chipping process generates a high rate transmitted signal. The symbols of this transmitted signal are much shorter / narrower (in time) than the symbols generated by a FHSS system transmitting the same data rate (see figure 1).

Obviously, a narrow pulse (DSSS systems use 11Mchips/sec over the air, i.e. pulses of 90ns width) is more sensitive to delays (shifts in time) than a wider pulse (FHSS systems transmitting at 3 Mbps use pulses of 330ns width) and as a result the FHSS systems have better chances to be undisturbed by the presence of multipath effects (see fig. 2).

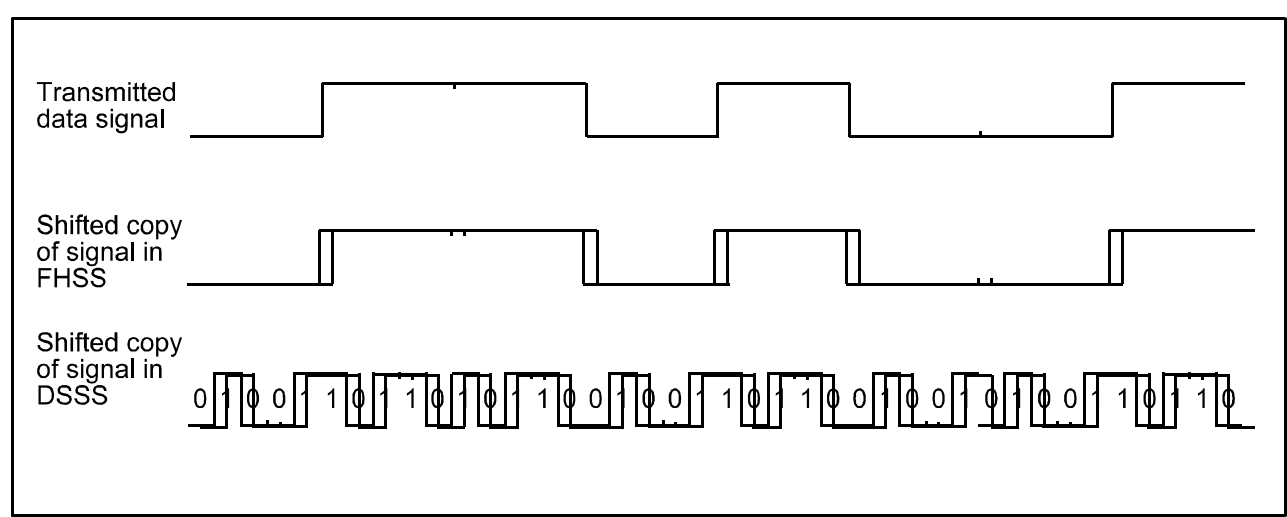


Fig 2 - Effect of identical shift in time on signals received in FHSS and DSSS systems

5.2.- Effect of multipath as seen in the frequency domain - fading

The multiple copies of the original signal arrive at the receiver with different instantaneous amplitudes and phases. The mixing of these copies at the receiver results in having some frequencies canceling one another, while other frequencies will sum up. The result is a process of selective fading of frequencies in the spectrum of the received signal.

(Supposing that the transmitted signal has the uniform spectrum of fig.3a, the spectrum of the received signal could look as in fig.3b).

FHSS systems operate with narrow band signals located around different carrier frequencies. If at a specific moment, the FHSS system is using a carrier frequency significantly faded as a result of multipath, the FHSS receiver could not get enough energy to detect the radio signal. (narrow rectangle in fig.3b). The resultant loss of information is corrected by re-transmitting the lost packets.

DSSS systems operate over wider bands, transmitting their signal over a group of frequencies simultaneously. As long as the average level within the wide rectangle in fig.3b is high enough, the DSSS receiver will be able to detect the radio signal. (However, even if the signal could be detected at the radio level better than in the case of FHSS, problems could occur when trying to convert the received radio signal into data bits, because of the time shift of the signals, as explained above). When the average signal in the working band is very low, the DSSS receiver will not get enough energy to detect the radio signal. The resultant loss of information is corrected by re-transmitting the lost packets.

The multipath effects explained above are a function of the transmission rate; 11 Mbps DSSS systems are much more sensitive to such effects than 2 Mbps DSSS systems.

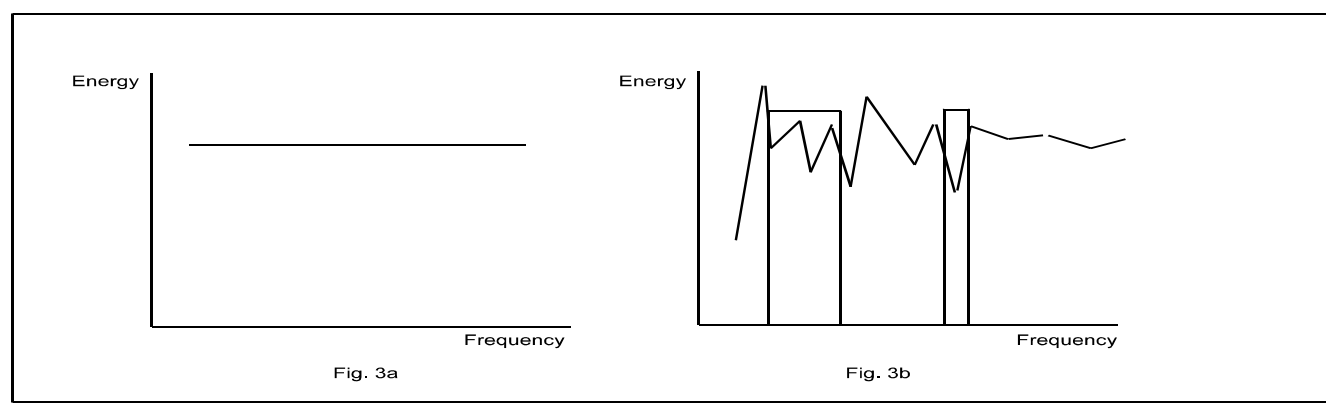


Fig. 3 - Fading effects for FHSS and DSSS systems

DSSS systems can accept delay spreads (generated by multipath) in the range of (typical values) about 500ns when operating at 1 Mbps, going as low as 70ns when operating at 11 Mbps. For a complete view of the issue, we should mention that typical delay spread in a room is in the range of 20 - 30 ns, while in a shopping mall with big open spaces and reflective surfaces, the delay spread reaches 200 - 400 ns.

We can conclude that DSSS is efficient as long as we can control somehow the delay spread; there are basically two ways of controlling the delay spread, dictating two different

types of applications in which one can take advantage of the high rate offered by DSSS, without paying the price of the multipath generated delay spread:

- a.- Allow multipath propagation, but keep the delay spread at low levels. This implies the use of DSSS systems in small areas, such as offices, for WLAN applications.
- b.- Significantly reduce the number of reflected paths, forcing all the energy to follow just a few paths of similar lengths, so that the multiple copies reaching the receiver will be shifted only by small amounts of time. This implies the use of DSSS systems with directional antennas, for point-to-point applications (building bridging, backhaul links in a cellular deployment, etc)

We shall also conclude that for long distances, point-to-multipoint topologies in reflective environments such as cellular deployments in a city, DSSS has no chance to survive, leaving FHSS the absolute winner, based on its famous multipath resistance.

6.- Time and frequency diversity

Both DSSS and FHSS retransmit lost packets, until the receiving part acknowledges correct reception. A packet could be lost because of noises or multipath effects.

This capability of a system to repeat unsuccessful transmissions at later moments in time is known as "time diversity".

DSSS systems use time diversity, but the problem is that they retransmit on the same 22 MHz sub-band! If the noise is still there or if the topography of the site did not change, and as a result the multipath effects will be again present, the transmission could be again unsuccessful!

The multipath effects are a function of frequency. For same topography, some frequencies encounter multipath effects, while others do not.

FHSS systems use "time diversity" (they retransmit lost packets at later moments in time) but they also use "frequency diversity" (packets may be retransmitted on different frequencies / hops). Even if some hops (frequencies) encounter multipath effects or noises, others will not, and the FHSS system will succeed in executing its transmission.

7.- Security

The issue: *Protecting the transmission against eavesdropping*

IEEE 802.11 compliant DSSS systems use one well known spreading sequence of 11 chips, and can modulate one of the 14 channel defined in the standard. As the sequence used is a priori known, the carrier frequency is fixed for a given system, and the number of possible frequencies is limited, it would be quite easy for a listener to "tune in" on the DSSS transmission. Message protection should be achieved by encrypting the data. This option increases the price of the product, while lowering its performance, because of the processing power needed for the encryption process.

In FHSS, the frequencies to be used in the hopping sequence may be selected by the user. In the unlicensed band, any group of 26 frequencies or more (out of the 79 available) is legal. To "tune in", a listener should know the number of frequencies selected in the system, the actual frequencies, the hopping sequence, as well as the dwell time! The FHSS modulation acts as a layer 1 encryption process. There could be no need for application level encryption!

8.- Bluetooth / IEEE 802.15 WPAN interference

The issue: *System behavior in the presence of Bluetooth / IEEE 802.15 collocated systems*

Bluetooth radio is a FHSS operating in the 2.4 GHz band, with a dwell time of 0.625ms (1,600 hops per second).

When DSSS executes a transmission, it is using 22 MHz for the duration of the transmitted frame. When FHSS executes a transmission, it is using 1 MHz for the duration of the transmitted frame.

The chances of having Bluetooth "hitting" the 22 MHz band used by DSSS are higher than the chances of it hitting the 1 MHz band used by FHSS.

Based on the above observation, we can conclude that, basically, DSSS is more sensitive to Bluetooth interference than FHSS.

9.- Summary

a.- Collocation / Aggregate Rate

DSSS biggest advantage over FHSS is its capability to provide rates of up to 11 Mbps. When covering the whole 2.4 GHz band, three systems may be installed, providing an aggregate rate of 33 Mbps. (Overall efficiency: $33\text{Mbps}/83.5\text{MHz} = 0.39$ bits/Hz). Additional systems, if installed, will share the spectrum with the already installed systems, lowering the overall aggregate rate / throughput because of collision occurrences.

In a 2.4 GHz FHSS synchronized environment, up to 12 systems can be collocated, providing an overall aggregate rate of 36 MHz (efficiency: $36\text{Mbps}/83.5\text{MHz} = 0.43$ bits/Hz).

In a licensed FDD FHSS synchronized environment, up to 6 systems may be collocated in a 10.5MHz band, providing an aggregate rate of 18 Mbps (efficiency: $18\text{Mbps}/10.5\text{MHz} = 1.7$ bits/Hz).

b.- Contiguous band

IEEE 802.11 DSSS needs 22MHz, contiguous. If such a band is not available, the system can not be operated. FHSS does not require contiguous band for correct operation. If some frequencies are not available (administrative reasons, multipath effects, noises, etc.), FHSS system could be set to use sequences that do not include the unavailable frequencies.

c.- Coverage

11 Mbps DSSS and 3 Mbps FHSS, cover more or less the same distances.

d.- Near / far problem

Present in DSSS, not critical in FHSS.

e.- Multipath sensitivity

DSSS is extremely sensitive, especially when operated at 11Mbps. To minimize multipath effects, point-to-multipoint topology systems have to be limited to small environments such as offices, while long distance systems are restricted to the use of directional antennas, limiting the DSSS technology to point-to-point topology applications.

f.- Bluetooth interference

FHSS are significantly less sensitive to Bluetooth interference.

D.- Conclusions

DSSS provides 11 Mbps capacity links, but it is a sensitive technology (collocation, multipath, near/far, Bluetooth). The most limiting factor, multipath, may be minimized by using the technology for short distances or in point to point applications.

FHSS provides only 3 Mbps capacity links, but it is a very robust technology, with excellent behavior in harsh environment characterized by large areas of coverage, multiple collocated cells, noises, multipath, Bluetooth presence, etc. The technology allows easy cellular point-to-multipoint deployment, providing excellent reliability.