A Comparison of Frequency Hopping and Direct Sequence Spread Spectrum Modulation for IEEE 802.11 Applications at 2.4 GHz

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Abstract

Two types of spread spectrum have been approved for use by the FCC in the unlicensed ISM band. The 802.11 WLAN committee establishing a global standard for wireless local area networks chose to allow the user to decide which one best fit his needs. This paper analyzes an approach to determining the performance tradeoffs so that a network engineer can make the decision. The approach is based on determining the maximum data flow per acre or the maximum number of networks per acre. The analyses done to date show that up to 13 collocated FH networks can be placed before network throughput peaks. Only 3 or 4 DS networks following the 802.11 standards can be collocated before the spectrum is filled. Does this mean that FH is the right choice? Let's examine further. The next group of 13 FH nets must be placed a long distance away before their interference with the first group is minimized. DS nets, on the other hand can be placed much closer to other DS nets on the same channel due the interference resistant nature of the DS waveform. From this reasoning, the maximum number of nets per acre or per square mile can be determined and a more intelligent choice made. Which is more important, a tight group of nets in your facility or a broad coverage area. Is the possibility that a neighboring facilities' network might interfere a concern? What else can be done for maximizing network throughput and minimizing latency. Which type spread spectrum is best for time bounded traffic? These questions are examined and some conclusions proposed.

1. Introduction

When it comes to the relative merits of (DS) versus frequency hop (FH) spread spectrum modulation schemes, the answer is: it depends. Choices depend on the particular implementation scenario. Hopefully, this article will dispel some of the confusion and allow engineers to pick the best choice for their particular job. Some observations are general, others relate to specific FCC part 15.247 requirements for the 2.4-GHz ISM band or to the portions of the draft IEEE 802.11 spec for interoperability in that band.

2. Spectral Density Reduction

Both DS and FH reduce the average power spectral density of a signal. The way they do it is fundamentally different and has serious consequences for other users. The objectives are to reduce both transmitted power and power spectral density to keep from interfering with other users in the band. The FCC has rules for both and you need to conform to these rules to stay legal and to avoid annoying other radio users.

DS spreads its energy by rapidly phase-chopping the signal so that it is continuous only for very brief time intervals. These intervals are called chips and are at least 10 times shorter than the data bits they chop. Thus, instead of all the transmitted energy being concentrated in the data bandwidth, it is spread out over the spreading bandwidth. The total power is the same, but the spectral density is lower. Of course, more channels are interfered with than before, but at a lower level. If the spread signal comes in under the noise level of most other users, it will not be noticed.

A DS spectrum exhibits discrete spectral lines that are related to the length of the sequence used for the spreading. In 802.11, the spreading uses an 11-bit barker sequence, so you would expect 11 lines (peak to null). Each line is further smeared by data scrambling, which spreads each spectral line and therefore fills in between the lines to make the spectrum more nearly continuous. The overall spectrum profile is $\frac{\sin X}{X}$, which is humped up in

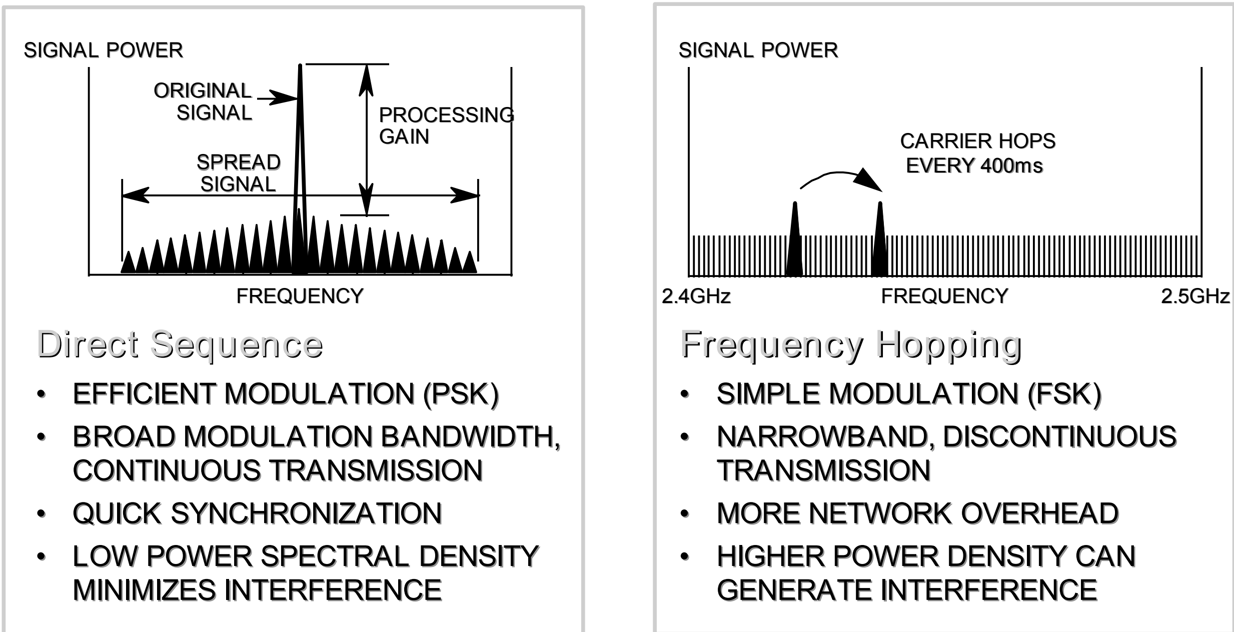


Fig. 1, DS and FH Modulation

the middle. Thus the interference is greatest at the channel center and it rolls off at the edges. Fig. 1 shows both DS and FH modulations.

Traditional FH signals lower their average power spectral density by hopping over many channels. During any one hop, however, an FH signal appears to be a narrowband signal. With slow hopping, the interference reductions are slight. A narrowband radio being interfered with will experience a pop or burst of noise when the hopper hits its channel. The main reason that 802.11 (and GSM) use hopping is not to minimize interference, but to share the pain of bad channels and to allow multiple uncoordinated nets to share the same spectrum.

If there are a lot of asynchronous FH radios using different hop sets in a given band, the overall effect is to spread out the energy over the whole band.

The spectrum of the FH signal modulated to conform to 802.11 concentrates the signal energy close to the channel center which is an inefficient use of the bandwidth. Additionally, FSK, is less power efficient than PSK, as will be shown, so more transmit power is needed. This power efficiency is further compromised with a low deviation ratio in order to conform to the FCC rules on occupied bandwidth. These rules state that the 20 dB bandwidth be less than 1 MHz. With the low deviation ratios required to conform to this specification for 802.11 FH WLANs combined with the inefficiency of GFSK modulation, the transmit power required to achieve a given range is substantially greater than for DS. Since the best overall interference reduction technique is to radiate less power, this gives an edge to DS.

3. Interference Susceptibility

So far, we've looked at the interference caused by spread-spectrum modulation schemes. The other side of the interference coin is that spread spectrum reduces the effects of other signals on the desired signal. The way FH and DS accomplish this is different, however. In DS receivers, the de-spreading operation multiplies the incoming signal by a local replica of the spreading waveform. This correlates with the desired signal to collapse it to the data bandwidth, while spreading all other signals. After the de-spread signal is filtered to the data bandwidth, most of the noise is outside this new narrower bandwidth and is discarded. Although, this helps with all types of narrowband and uncorrelated interference, it has no advantage for wideband interference such as the microwave oven, since spread noise is still noise and the percentage that falls within the data bandwidth is unchanged. One drawback of DS is that the bandwidth over which the interference is damaging is wider than for a non-spread system. This requires that the channels be spaced wider and well away from high-power signals such as broadcast stations.

The FH signal is agile and does not spend much time on any one frequency. When it hits a frequency that has too much interference, the desired signal is lost. In a packet switched WLAN network, this results in a re-transmission, hopefully on a clearer channel. In a fast enough FH system, the portion of signal lost may be recovered by spreading the data energy out in time through forward error coding, but only if the FEC spans more than one hop in time. For the very low hop rates suggested for 802.11 WLANs, forward error coding is not practical.

The ability of any signal to tolerate interference is also related to the minimum system Eb/N0. A lower Eb/N0 means that the system can tolerate a dirtier signal. Therefore, the power efficiency of the modulation should be as high as possible. The standard is BPSK, which is recognized as efficient and robust. DS signals usually use BPSK, since there is no jamming resistance advantage to QPSK, but 802.11 specifies QPSK at 2 MBps to maintain the FCC-mandated 10-dB minimum processing gain. It doesn't make any difference, however, since the required Eb/N0 doesn't change.

If the 802.11 DS system operates at 13.4 dB Eb/N0 as discussed below, it can tolerate interference up to a level -3 dB relative to the desired signal. (This also means that there is no code division multiple access (CDMA) capability, since the processing gain and required Eb/N0 do not allow another signal of the same power to occupy the same channel.)

For the purposes of this discussion, FH is narrowband GFSK, since it doesn't hop during a packet. There is no processing gain during a packet and the signal is less power efficient. IEEE 802.11 allows 24 dB Eb/N0 for 1 MBps (and 29 dB for 2 MBps). The theoretical performance is only 5 dB better than this , so the 1-MBps FH system can only tolerate in-band interference up to -19 dB relative to the signal carrier. Compared to DS, this is 16 dB less tolerant. However, FH is more tolerant of interference that occurs outside its 1-MHz signal bandwidth, since the receiver filters will reject it.

To summarize, broadband noise affects both FH and DS similarly, so the system with the better Eb/N0 (i.e. DS) will be more immune. Narrowband interference will have a more severe impact on an FH signal than on a DS signal if it is on the same channel but a less severe impact if it is on a different channel

4. Near/Far Ratio

Near/far effects are often put forth as a limitation for DS. However, they also affect FH and narrowband signals. The term near/far refers to the effects on a receiver from a transmitter operating on its frequency that is nearer to it than the transmitter you want to receive from. DS signals can operate with much better near/far ratios than FH signals since they have processing gain. On the other hand, since they operate over a wider bandwidth, they have to deal with more extraneous signals. On a given channel, distant FH signals are blocked by nearer signals, but, theoretically, as long as they can hop to another channel and re-transmit they can get around the problem.

5. Multipath

DS suppresses multipath by decorrelating the delayed signal. When multipath signals are delayed by more than one chip relative to the direct-path signal, the direct signal has a processing gain advantage. When the multipath signal arrives within a one-chip delay, this creates fading. That is, the direct signal can be either enhanced or suppressed. Therefore, for DS to achieve significant multipath rejection, its bandwidth must be wider than the coherence delay of the environment. For 802.11 the chip rate is 11 MCps, so the coherence interval is 1/11 M, or about 91 ns. This will provide good multipath protection in large warehouses, but less in office buildings.

For FH, multipath signals always arrive within the signal's coherence interval and cause fading. The coherence interval, in this case, is the symbol duration. This causes some paths to be unusable, and that's why this waveform is hopped.

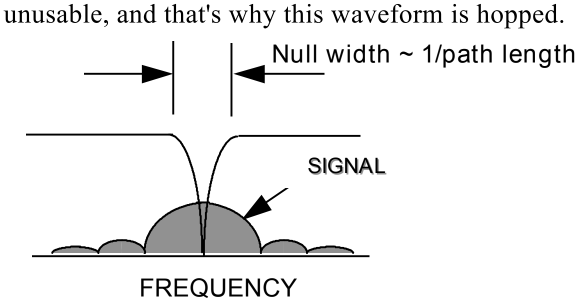


Fig. 2, Channel Response

One way to look at the multipath effects is to look at the spectral nulling that occurs in the channel response.

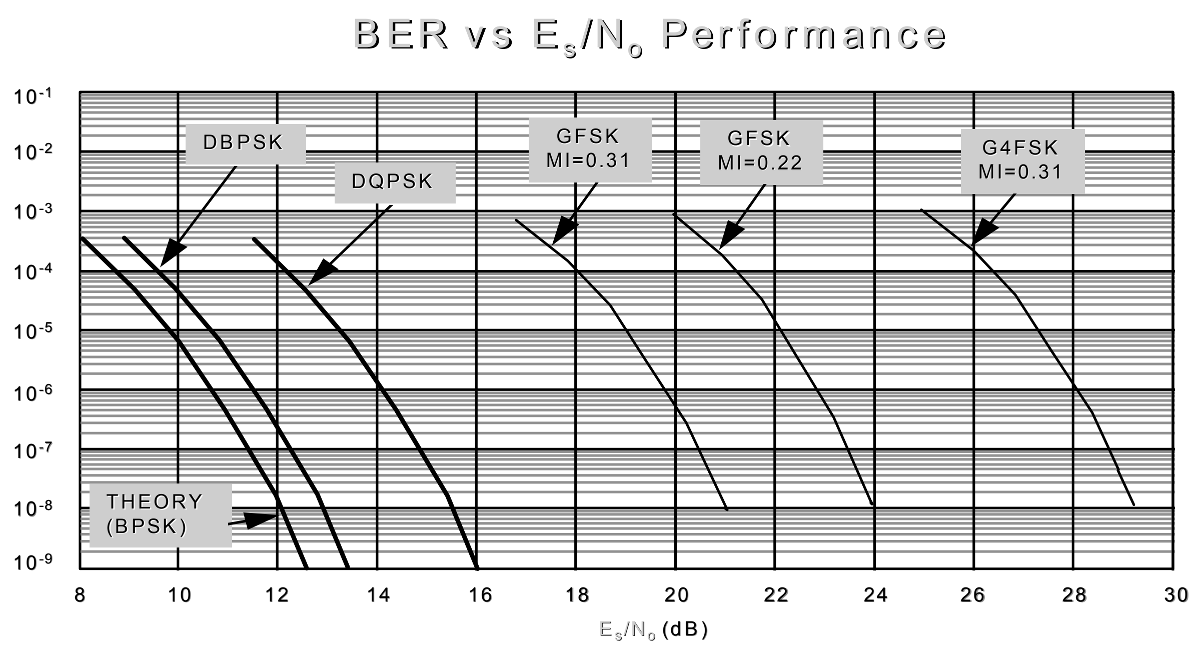
When the direct path and indirect path signals are short, the spectral null that occurs is broadband and can take out a significant part of the DS spectrum. For longer paths, the spectral null is narrower in bandwidth and can take out less of the DS energy. For FH, the spectral null takes out most of the signal energy since the signal is narrowband and falls well within the null bandwidth. Again, DS is effected less but over a wider range of frequencies than FH.

6. Comparison of DPSK and GFSK Modulations

BPSK and QPSK are modulation schemes that are well known to give close to the best power efficiency available along with reasonable bandwidth efficiency. The bandwidth efficiency is discarded with DS spreading in order to lower the power spectral density. There are additional losses with differential encoding and scrambling that cause a loss in performance due to error extension. This means that for every error that occurs, the differential decoding extends that to 2 errors and descrambling further extends that to 6 errors. Thus, you can expect the theoretical 9.6 dB Eb/N0 performance for 10^{-5} BER to be degraded to 10.6 dB (plus implementation losses). The Harris Prism™ demodulator (HFA3824), for example, has 2.8 dB implementation loss, for a net 13.4-dB Eb/N0.

The 802.11 FH narrowband GFSK signal, which is power inefficient within the given constraints, requires 19 dB Eb/N0 when used with the greatest modulation index that will fit in the allocated bandwidth. Based on FCC rules, the bandwidth allowed the FH signal is 1 MHz at -20 dB. This is too narrow for efficient transmission at 1 MBps, and is even more inefficient for the 4-FSK used for 2 MBps, because the allowed deviation ratios are minuscule. This does, however, keep the overall spectrum occupancy low and allows more channels in a given band. In a 4-FSK demodulator that uses conventional limiter/discriminator techniques without coding, the expected power efficiency performance will be <u>much</u> worse than QPSK.

The curves in Fig. 3 show the Es/N0 performance of DBPSK, DQPSK, GFSK, and G4FSK. Two modulation indices for GFSK are



The performance of the DBPSK and DQPSK include error extensions from differential encoding and scrambling

Fig. 3, Performance of DBPSK and GFSK

shown. They represent the minimum modulation index and the nominal index. A systems designer would use the largest modulation index that will still allow the unit to pass the FCC bandwidth requirement.

7. Ability to Expand to Higher Data Rates

The DS signal can achieve higher data rates by increasing the modulation complexity or increasing the clock rates. Each increase in the data rate will, however, require a corresponding increase in the transmit power or a cut in range. FH has few options for data rate increases. 8-FSK, with an extremely small deviation, is not feasible (Eb/N0 ~ 36 dB). FH would need a wider bandwidth allocation to achieve any higher data rate, but the wider bandwidth would cut the number of channels to hop in. This would in turn cause more collisions unless the number of collocated nets was reduced. This is a non linear problem, so the number of nets that could be collocated would reduce to about 3 if the number of hopping channels were reduced to 20.

8. Transmit Power

DS, being more power-efficient should require less transmit power. This is tempered, however by the need to minimize the transmitter cost by avoiding post-modulation filtering. This means you cannot fully utilize the saturated power of the power amplifier. To keep the spectrum shape, the DS designer must cut back the power from the amplifier by 3 to 6 dB. Since the basic DS waveform is more power efficient than FH, this makes DS more efficient in PA utilization usage than FH at 1 MBps. At 2 MBps, the extremely low efficiency of the 802.11 FH system requires a significant boost in transmit power, giving a clear edge to DS. The FH signal is very constant in amplitude and can fully utilize the saturated power amplifier output, but its lower modulation power efficiency more than outweighs this advantage.

Under IEEE 802.11, the DS signal is spread over 22 MHz, lowering its spectral density. This allows it to use higher transmit power without interfering with other users of the band. The drawback is that it can interfere with more users over the wider bandwidth. If power spectral density is the constraining issue, DS clearly has the edge over FH.

9. Multiple Signal Operation

As noted in section 3, an 802.11-conforming DS network cannot employ CDMA because the processing gain and required Eb/N0 do not allow another signal of the same power to occupy the same channel. Thus, only 3 (4 with aggressive filtering) networks can operate collocated. These can operate on separate channels (for example 1, 6, and 11) at the same site, that is, in the same room . FH, on the other hand, allows multiple uncoordinated signals to be collocated. Up to 15 FH nets can be collocated before the interference is too great. (This is based on the probability of collisions where two of the nets choose the same one of 79 channels at the same time.) When the probability of collisions gets too high, network throughput suffers. A recent paper by Lucent Technologies[i] showed that effective throughput of FH peaks at about 13 nets. The aggregate throughput of these 13 collocated FH nets is less than the aggregate throughput of the 3 collocated DS nets because they are interfering with each other and only operate at 1 MBps.

DS nets on the same channel can be placed much closer together, since the signaling is more robust, allowing more total networks and therefore more capacity in a given area. Section 3 showed that an FH system for 802.11 needs 7.6 dB more transmit power to achieve the same range and has an 18 dB disadvantage in interference rejection. Thus the FH nets have to be placed 25.6 dB further apart. So, when combined with the FH advantage of 5:1 (7 dB) in channels collocated, this translates to 18.6 dB fewer nets in a given area. How this dB number relates to the number of nets is dependent on the propagation conditions.

In a real world application, for example, an FH system can support a higher density of nets (access points) in a single room—up to 13, while DS allows only three to four. However, the next group of nets in an FH system has to be much further away (the signal has to be 19 dB down!) or both groups suffer loss of throughput. DS groups of 3 can be much closer together, allowing more total nets and more total throughput per hectare.

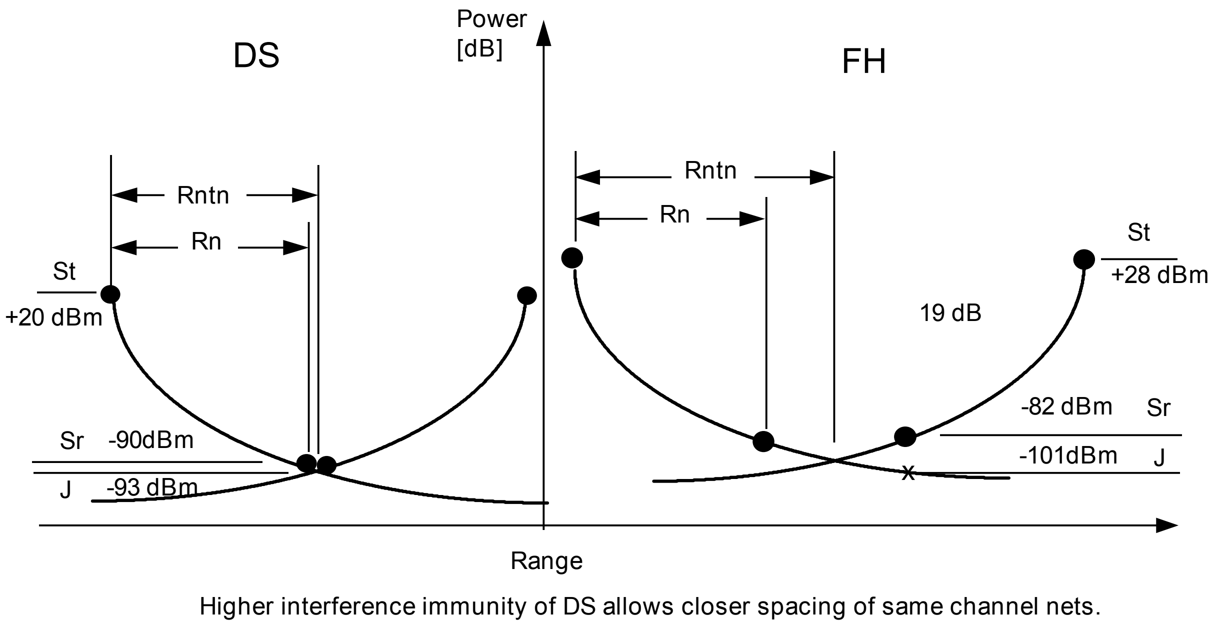


Fig. 4 Ranges of DS and FH

A system designer wouldn't usually place the nets in such an arrangement, but the fact remains, if two nets are using the same channel or hop set, they must be placed much farther apart in FH than in DS because the zone of interference is much larger.

Fig. 5 shows how the nets can be packed and defines the net range and . the net to net spacing diagramatically. For DS, the network range is dictated by 110 dB of path loss which is the ratio of the +20 dBm transmitted signal to the -90 dBm level of the minimum receive signal. Various studies

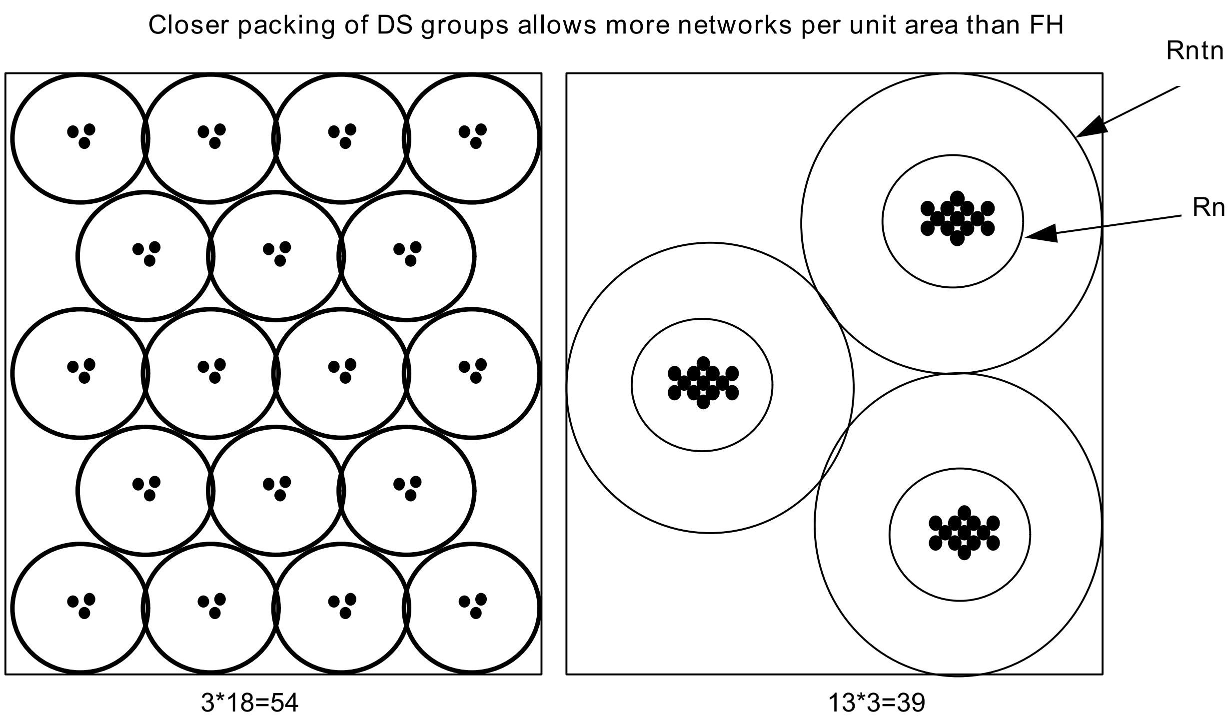


Fig 5, Packing of Networks

of indoor range losses put the average propagation loss at range cubed. It is well known that the loss exponent is a function of range, and some studies show the loss to be 30 dB per 100ft. after the first 50 ft., but this would complicate the message here. The range to the next net (net to net spacing) is dictated by the maximum interference signal, which has been stated to be -3.2 dB relative to the desired signal in DS. Thus, the net to net spacing is slightly larger than the net range.

For FH, the required transmit power to reach the same range is 8 dB higher, since the receiver is that much less sensitive. The net to net spacing is also larger since the interfering signal must be reduced to -19 dB relative to the desired signal. This is due to the combined effects of the higher Eb/N0 and not having processing gain. In dB terms, the FH net to net spacing is 25.6 dB greater than DS.

10. Synchronization and Timing.

DS is self-synchronizing, since it employs a very short code that can be searched with a time-invariant matched filter. Thus, a DS radio, while roaming, can rapidly change to another channel and join another net, assuming that it knows the frequency to tune to. If not, it must scan all frequencies and stay on each until a signal is transmitted on that channel. The usual beacon interval is 100 ms, so that is the time it should stay on each of 12 frequencies to search for all active nets. Thus the total search time is 1.2 s. The FH system search procedure allows the mobile station to sit on any one frequency and wait for a signal or beacon. If this is a bad frequency for this net, it may have to move to another and sit and wait. This is because the FH system has many channels to search and it is not feasible to perform the search in parallel. If the station scans for energy, it may or may not improve its chances since any one channel might not have energy while it is looking. Once a station hears a beacon, it gets the network timing and the hopping sequence to use. Under FCC rules, FH has been denied a calling channel and a global timing reference, constraining FH's ability to achieve rapid roaming synchronization. Thus, roaming with FH will require a longer time to achieve net switching.

In time bounded services, latency must be minimized. Various studies have shown that 30 ms is the most that can be tolerated with voice traffic. In an FH net, if the channel is jammed, the next available retransmission time on a clear channel may be 400 ms away. In addition, the rules state that if a packet can't be completed within the current hop, it should be held until the next hop. These are clearly unacceptable for time bounded services. No such timing constraints exist for DS, but if a DS station is jammed, it is jammed until the jammer goes away.

11. Capacity

The network protocols for DS and FH are slightly different to accommodate the peculiarities of each physical layer. In particular the interframe spacing and Slot Times are different, and recommended packet sizes are smaller for FH (400 bytes vs 1000). The net effect is a slight edge for DS in overall throughput at 1 MBps. The 2 MBps rate is optional for FH and required for DS. If throughput is of greatest concern, DS is the winner.

12. Implementation

There is a small inherent advantage to FH in hardware cost between the two modulation schemes. FH can be handled with a simple analog limiter/discriminator receiver while DS requires complex baseband processing. DS requires higher logic speeds and more complex processing, but this is not the strong cost driver it once was. With highly integrated chipsets, this will not be the major driver. The FH scheme chosen by the 802.11 committee has an additional complication for DC bias suppression, but FH still requires less processing than DS.

13. Power Consumption

Power consumption is a key consideration for the network engineer. The basic technology for DS consumes slightly more power than FH due to higher logic speeds and more complex processing. On the other hand, since the FH nets will most likely operate at 1 MBps and the DS nets at 2 MBps, there will be a power savings with DS from the shorter duration of the packets and the lower network overhead. This results in longer transmit times and less time to be in sleep modes.

14. Summary

When it comes to the relative merits of FH or DS spread spectrum modulation schemes, the answer is: it depends. The choices depend on the particular implementation scenario.

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[i] A. Kamerman, "Spread Spectrum Techniques Drive WLAN Performance." Microwaves & RF September, 1996, pp. 109-114