IEEE P802.11
Wireless LANs

Proposal for a second letter for filing in the proceedings of FCC OET Docket No. 99-231

Date: September 14, 1999

Authors:
Jim Zyren, Intersil, Jan Boer, Lucent Technologies, Donald C. Johnson, WLAN Consulting,

Summary

Attached is a proposal for a second letter for filing in the proceedings of the FCC in NPRM, OET Docket 99-231. This letter provides additional substantive material to support the statements in the first letter filed on August 19, 1999.

The text has been made by the experts mentioned above, based on submissions and discussions held in meetings of the ad-hoc regulatory group on Monday September 13, 1999.

The intention is to discuss the text on the Wednesday, September 15, 1999 meetings of the ad-hoc regulatory group with the aim to recommend an 802.11 and 802.0 combined e-mail ballot.

Sept 13, 1999

Magalie R. Salas, Esquire
Secretary
Federal Communications Commission
445 12th St. SW
Washington DC 20554

Re: Amendment of Part 15 of the Commission's Rules for Spread Spectrum Devices, ET Docket No. 99-231

Dear Ms. Salas:

IEEE 802, the LAN/MAN Standards Committee ("the Committee"), is writing in regard to ET Docket No. 99-231: Amendment of Part 15 of the Commission's Rules for Spread Spectrum Devices. On August 19, 1999, the Committee submitted an ex parte letter~~comments~~ in this proceeding expressing opposition to the proposed rule~~s~~ changes which would allow wider channels for FHSS systems as described in the Notice of Proposed Rule Making (the "Notice") in this proceeding. Since that time, the membership has continued to ~~analyse~~ analyze the proposed rule changes. The Committee respectfully submits these additional comments in this proceeding.

The Institute of Electrical and Electronics Engineers, Inc. (IEEE) is a USA-based international professional organization with more than 325,000 members representing a broad segment of the computer and communications industries. IEEE 802.11, a chartered Working Group under the Committee, has developed a standard for Wireless Local Area Networking (WLAN) in the 2400-2483.5 MHz band ("the 2450 MHz band"). The number of individuals and corresponding company sponsorships in the IEEE 802.11 Working Group evidences the strong interest in wireless local area networking. The Working Group currently has over 200 members employed by 86 companies

Regarding the issue of Rule changes to increase the channel width of FHSS radio channel width, the Committee has already commented on a number of points in the correspondence of August 19, 1999. These comments are summarized below:

a. The use of heavily overlapped channels for Wide Band Frequency Hopping (WBFH) systems will result in significantly increased interference among systems employing this method of channel selection.

b. Increasing hop rate for WBFH systems will not reduce the interference threat to other users of the band. In fact, this measure will actually increase interference with other users~~a~~. We note that there is no regulatory prohibition against the use of systems which have higher hopping frequencies, but we are of the opinion that the Commission should not make higher hop rates mandatory.

c. In addition, we find that the proposed reductions in transmitted RF power for WBFH systems are not adequate to ensure that existing systems do not suffer increased interference.

d. We further note that the resulting increase in interference described above will hinder market acceptance of high speed wireless networking product which operate in the 2.45 GHz ISM band.

The Committee would like to make the following additional comments relating to proposed changes in FHSS operating rules:

a. Direct Sequence Spread Spectrum (DSSS) systems were able to achieve higher throughput without requiring a change in the Commission's Rules. More importantly, higher data rates were achieved with no change in the Power Spectral Density (PSD) of the DSSS waveform. Therefore, there is little or no impact in terms of increased interference with other users of the band.

b. In the Notice, the ~~FCC~~ Commission (please be consistent) asks for comments on (spell out because first time used) HWN's assumption that wide band frequency hopping systems will be unable to consistentl~~e~~y achieve substantially greater data rates than 1 MHz systems. This comment by IEEE P802.11 (this reference is unclear, which comment, comment a?) supports HWN's view in this matter. The adverse effects of multipath on WBFH system throughput are described in detail in the following paragraphs.

Currently employed frequency hopping systems complying with Part 15 employ 2 or 4 level FSK modulation (1 or 2 Mbit/s) and have a 20 dB bandwidth of 1 MHz. The benefits of these systems are that they can be manufactured at relatively low cost because they have nonlinear signal processing components, while they maintain a reasonable performance in a multipath environment. The narrow band FH systems work satisfactorily in environments where the delay spread is in the range of 100-200 nanoseconds which are characteristic of large retail stores and manufacturing facilities.

The FH systems work because of the frequency diversity capabilities inherent to hopping. Narrow band frequency hoppers experience this level of delay spread as flat fades. If, because of a fade no transmission is possible at the particular frequency, the chance to be in a fade again at the next hop (next 1 MHz frequency channel) is small. By widening the bandwidth of the frequency hopper to 3 or 5 MHz, the hopper has to deal with in band multipath distortion instead of flat frequency fading. At the next hop (frequency) the chance that no transmission is possible because of multipath remains high.

There is a linear relationship between the intersymbol interference caused by multipath and the symbol length; widening the bandwidth of a transmission system with a factor x (without changing the modulation method) makes the system x times more susceptible to multipath. For a 5 MHz wide frequency hopping system employing 2 or 4 level FSK this means that the system can only tolerate delay spread spreads of up to 20-40 nanoseconds. These delay spreads are characteristic of ordinary rooms. Further, in low cost implementations, this amount of in band distortion can be introduced by the transmit and receive filters, thus reducing tolerance to multipath to almost zero. Such systems would not be viable from a user point of view.

From above reasoning we conclude that a 5 MHz wide frequency hopper employing 4 level FSK will not work in a normal environment. To get data through the frequency hopper has to fall back to a narrower bandwidth with a lower data rate.

Of course, a wide band FH system can be designed to be more robust against delay spread. If the same modulation method is maintained, then a form of equalisation is necessary. Apart from the higher amount of (signal) processing, which increases component cost, equalization also requires linear processing in both transmitter and receiver increasing the cost of (linear) components.

Other modulation methods that are more robust against multipath can be employed in wide band FH systems. These methods however require linear components and a high amount of signal processing.

To bring the delay spread robustness for a wide band frequency hopper to the level required for normal operation, there is a cost (nothing is free). The required components (linear power amplifiers, linear receive functions (AGC), DSP components) bring the cost to the level of currently employed direct sequence systems or higher. Direct sequence systems are running at 11 Mbit/s and with adequate robustness against delay spread effects. The costs of this type of equipment are decreasing rapidly (refer to the Apple's Airport product announcement in August this year).

Based on above arguments, it can be concluded that the HomeRF Working Group claim that future wideband FH services can be implemented at lower cost and with greater multipath robustness than can current DS systems operating at comparable speeds does not hold and is misleading.

IEEE 802.11 also submits additional studies in support of the statements made in the earlier letter of August 19, 1999.

1.) The document "*Interference Potential of WideBand Frequency Hopping Systems on Packet Data Systems*" includes an analysis of the effect of the power level of the WBFH systems.

2.) The document "Effects of WBFH Power Reductions and Hop Rate" presents analysis results showing that increasing hop rate increases the collision rate with both DSSS and conventional narrowband FHSS systems. The effects of proposed power reductions is also described in detail.

In summary, the Committee opposes the changes to the operating rules for FHSS systems as described in the Commission's Notice of Proposed Rule Making in this proceeding. The Committee reiterates comments made in the August 19, 1999 letter to the Commission and additionally concludes that WBFH system will suffer severe impairment due to multipath channel distortion. The Committee is also forwarding two papers as described above in support of our earlier comments in this matter.

Respectfully,

James T. Carlo (jcarlo@ti.com)
Chair, IEEE 802 LAN/MAN Standards
Texas Instruments
9208 Heatherdale Drive
Dallas TX 75234

Vic Hayes (vichayes@lucent.com)
Chair, IEEE 802.11, Wireless LANs
Lucent Technology
Zadelstede 1-10
3431 JZ Nieuwegein, the Netherlands

cc:

Chairman William E. Kennard
Commissioner Susan Ness
Commissoner Harold Furchtgott-Roth
Commissioner Michael K. Powell
Commissioner Gloria Tri~~ia~~stani
Dale Hatfield
Julius P. Knapp
Neal L. McNeil
Karen Rackley
John A. Reed
Anthony Serafin

Annex 1

Interference Potential of WideBand Frequency Hopping Systems on Packet Data Systems

Date: September 13, 1999

Author: Donald C.Johnson
WLAN Consulting,Inc.
Phone: 937 434-8389
Fax: 937 434-3287
e-Mail: JohnsDB@aol.com

1.0 Abstract

The effect of modifying the 47 CFR Part 15.247 frequency hopping spread spectrum rules to permit a wider bandwidth is investigated relative to the interference potential on packet data transmission systems that conform to the current rules. The rules modification would permit WideBand Frequency Hopping (WBFH) systems with bandwidths of 3 MHz and 5 MHz in addition to systems operating under the current rules that limit the bandwidth to 1 MHz.

The probability of a WBFH transmission mutilating a wireless data packet is investigated in terms of the WBFH and victim power levels, the WBFH bandwidth, the duration of the victim packet interval and WBFH hop interval and potential victim receiver parameters. A WBFH system operating in accordance with the proposed revised rules and a potential victim wireless packet data system conforming to the current rules are considered to operate in the same area. The configuration analyzed consists of a victim packet data system operating in a centralized mode and an interfering WBFH system with transmitters evenly distributed within and around the victim system communication cell. The proportion of WBFH transmitters that create packet errors in the victim receiver is analyzed.

It is shown that increasing the frequency hopping rate increases the probability of interference to packet data systems. The wider bandwidth would, of itself, increase the interference probability, but it would also permit a higher hoping rate. The proposed rules modification would place a lower limit on the hopping rate, but would not impose an upper limit. The potentially higher hopping rate would further increase the interference probability.

It is shown that increasing the bandwidth of frequency hopping systems to 3 or 5 MHz greatly increases the interference to 1 MHz bandwidth frequency hopping packet data systems. The increase would require the WBFH system to use a power level as much as 20 dB below the 1 MHz system to offset the effect of the wider bandwidth alone. The potential increase in frequency hopping rate also produces a like factor.

The effect on direct sequence packet data systems is less, but is nevertheless significant. It is shown that the change would cause a 13 to 15 dB effect on a packet data system such as one conforming to IEEE p802.11. That is, the WBFH power level would have to be decreased by 13 to 16 dB to have the same interference effect on this system as does a 1 MHz bandwidth frequency hopping system.

2.0 Packet Overlap Dependence on Bandwidth and Hop Time

The relative overlap probability will be investigated independently of the relative power level of the interfering and victim systems. That is, it will be assumed that there are a fixed number of WBFH transmitters near enough to the packet receiver to interfere and that this number does not vary with bandwidth. This will later be expanded to investigate the effect of the relative power levels of the two systems, including the bandwidth effects on the interference power level.

Define the following parameters:

- B_i = Bandwidth of the interfered signal.
- B_h = Bandwidth of the wideband frequency hopping (WBFH) system (1, 3 or 5 MHz)
- B_{ih} = The interference bandwidth, the difference frequency range over which the WBFH signal interferes with the victim receiver. $B_{ih} >= B_i + B_h$ [1]
- B_t = Total bandwidth of the WBFH system (75 to 85 MHz.)
- H_t = WBFH hop time
- P_t = Packet transmission time.

Refer to figure 2-1 and consider a single active wideband WBFH transmitter within range of a LAN packet receiver. If one or more on-frequency hops start in the interval $H_t + P_t$, then overlap occurs.

Probability hop is on the packet frequency = $\dfrac{B_{ih}}{B_t} \approx \dfrac{B_i + B_h}{B_t}$

Mean time between start of on-frequency hops = $\dfrac{H_t B_t}{B_i + B_h}$

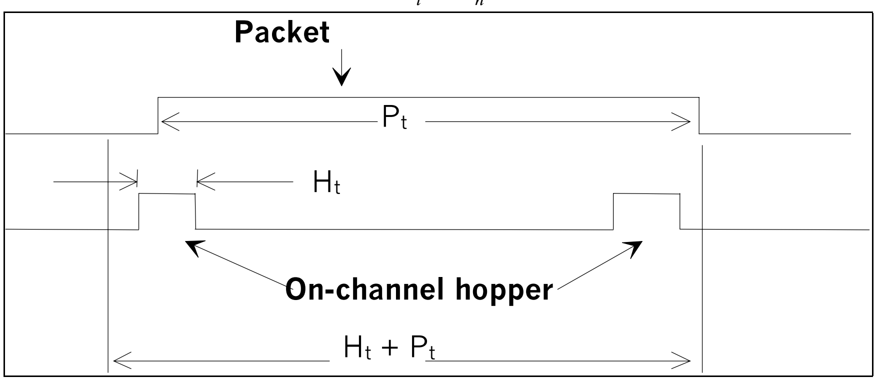

Figure 2-1. Illustration of WBFH Overlap with LAN Packet.

The mean number of hops that start in the interval $H_t + P_t$ equals the duration of this interval divided by the mean duration between hops. Let this mean number be m_1, then

$$m_1 = \left[\frac{H_t + P_t}{H_t}\right]\left[\frac{B_{ih}}{B_t}\right] \approx \left[\frac{H_t + P_t}{H_t}\right]\left[\frac{B_i + B_h}{B_t}\right]$$

If there is one active WBFH system in range of the packet LAN receiver, then m_1 is the probability of overlap. If there are more than one active WBFH system in range, then the overlap probability can be modeled as a binomial probability function with m_1 equal to the probability of "success" on each try (one try per frequency hop system). With N such systems in range, the overall probability of overlap is

$$\Pr(\text{overlap}) = 1 - (1 - m_1)^N$$

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[1] Reference 1 shows some measurements of the interference bandwidth for two frequency hoppers using the modulation technique employed in the IEEE p802.11 frequency hopping wireless LAN. In the case of both the 1 MHz and 5 MHz bandwidth frequency hoppers the 3 dB interference bandwidth is approximately equal to the sum of the 20 dB bandwidths. The frequency hopping systems with a 20 dB bandwidth of 1 MHz had a 3 dB interference bandwidth of 2 MHz and that with the 5 MHz bandwidth had a 3 dB interference bandwidth of 9.5 MHz.

The process can be modeled as a Poisson process if the mean number of overlaps is very low relative to the possible number. With N active WBFH transmitters, the maximum number of hop signals that can start within the overlap interval is $\left(2+Int\left(\frac{P_t}{H_t}\right)\right)N$ where *Int*(x) means the largest integer less than or equal to x. The mean number is m_1N, thus, if $m_1 << \left(2+Int\left(\frac{P_t}{H_t}\right)\right)$ the Poisson process should be a good approximation.

In the more general case there is a larger population of WBFH transmitters, each with a relatively low probability of being active. Thus, the mean number of overlaps is very low compared to the possible number and the Poisson process applies.

If there are M frequency hopping transmitters in range and the mean probability that a transmitter is active is p, then N is a random variable with mean Mp and the Poisson distribution is appropriate.

Let λ be the mean number of on-frequency hops starting in the overlap interval. In the former case $\lambda_1 = Nm_1$ and in the second case $\lambda_2 = Mpm_1$. thus, in the more general case

$$\lambda = \lambda_2 = Mp\left[\frac{H_t + P_t}{H_t}\right]\left[\frac{B_{ih}}{B_t}\right]. \qquad (2\text{-}1)$$

Using the Poisson approximation, the probability of at least one overlap is

$$\Pr(\text{overlap}) \approx 1-\varepsilon^{-\lambda}$$

Since

$$1-\varepsilon^{-\lambda} = \lambda - \frac{\lambda^2}{2} + \frac{\lambda^3}{6} - - - -,$$

if $\lambda << 1$ then $1\text{-}e^{-\lambda} \approx \lambda$ and

$$\Pr(\text{overlap}) \approx \lambda \text{ if } \lambda << 1.$$

Normally the packet error rate must be less than 0.1 for a good quality packet LAN.

The information throughput demand tends to track the capability, thus the factor Mp will be relatively independent of the frequency hopping bandwidth.

Two facts are obvious from the expression for λ.

First, the overlap probability, and thus interference probability is increased with short hop times. The first bracketed expression approaches the value P_t/H_t as the hop time approaches zero. This would imply that a minimum hop time would be a better requirement than would be a maximum hop time. Otherwise, a contest is likely to develop to optimize interference robustness by shortening the packet times. Wireless packet data systems are inefficient with very short packet times, thus a contest to match packet times to hop times would lead to inefficiency.

Second, increasing the frequency hopping bandwidth increases the interference potential. This is particularly severe when the victim bandwidth is low, as is the case for packet data frequency hopping systems conforming to the present bandwidth rules (such as those operating in accordance with the IEEE pp802.11 standard). The current rules require a 1 MHz maximum 20 dB bandwidth. Two frequency hopping systems complying with these rules have an interference bandwidth of less than 2 MHz even if the frequencies do not match. Widening the frequency hopping bandwidth to 5 MHz would increase the number of interferers by a factor of at least 3.

Some examples of the overall effect are presented in section 5.

3.0 The Effect of the Interference Power Level

The number of transmitters in interference range of a victim packet transmission system operating in a common area depends upon the power level difference between the potential interferer and the potential victim. Lowering the WBFH power level is proposed as a means of equalizing the increased interference effect of a wider frequency hopping bandwidth. The relative power level effect on interference will be investigated here.

A transmitter will interfere with another system receiver if it is within the range in which the interference power it produces in the receiver exceeds the required carrier to interference power margin. This interference level depends in turn on the power level and transmission distance of the potentially interfered system. If the deployment area of the interferer and victim system is smaller than the median interference area, then the majority of the transmissions will create interference. A reduced power level only helps to the extent that the reduced level reduces the interference area relative to the deployment area.

The dependence of the interference range on power level will be established.

Define the following additional parameters:

p_1 = the transmit power of system 1 (the interferer system)
p_{21} = the transmit power of system 1 within the bandwidth of system 2 (the victim system)
p_2 = the transmit power of system 2
γ_i = the required signal power to interference power ratio of system 2
c = the system 2 transmission range (the communication range)
r_i = the system 1 transmission range (the interference range)
a_{22} = the transmit to receive power ratio at distance c (the system 2 range)
a_{21} = the transmit to receive power ratio at distance r_i (the system 2 to system 1 range)
α = the attenuation exponent.
β = the proportion of interferer power within the bandwidth of the victim receiver.

$$\beta = 10Log\left(\frac{B_h}{B_i}\right) \quad B_h > B_i$$

$$\beta = 0 \quad otherwise.$$

In the following, upper case letters will represent decibel quantities and lower case letters will represent ratios. That is,

Γ_i = $10Log\gamma_i$,
A_x = $10Loga_x$ and
P_x = $10Logp_x$.

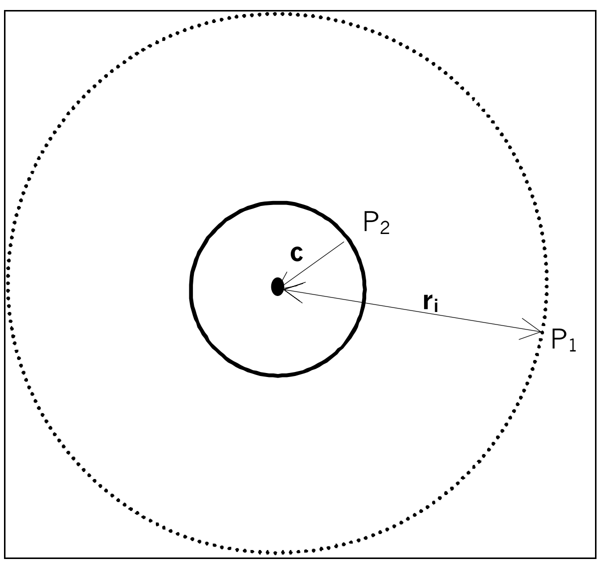


Figure 3-1. Illustration of the Interference Range Compared to the Communication Range

The dotted circle in figure 3-1 represents the interference range of a transmitter of power level P_1 to a receiver centered in a LAN cell when the transmission distance is c. The ratio of the interference range r_i to the communication range c will be examined.

The necessary condition for creating interference is

$$\frac{p_{21}a_{22}}{p_2 a_{21}} \geq \gamma_i .$$

The attenuation exponent is commonly modeled as having a value of 2 up to a range of 5 to 10 meters and a larger value α beyond this range. In this model, with the α = 2 range at 10 meters, the attenuation in deciBels can be expressed as

$$A(r) = A_f - 10\alpha + 10\alpha Log r + A_v, \qquad (3\text{-}1).$$

in which A_f is the attenuation at 10 meters and A_v is an approximately normally distributed random component with mean zero.

The condition for avoiding interference can be expressed in decibel quantities and reduced to

$$10\alpha Log r_i = 10\alpha Log c + P_{21} - P_2 + \Gamma_i + \left(A_{v2} - A_{v1}\right). \qquad (3\text{-}2)$$

On further reduction

$$\frac{r_i}{c} = 10^{\frac{P_{21} - P_2 + \Gamma_i}{10\alpha}} * 10^{\frac{A_{v1} - A_{v2}}{10\alpha}} \qquad (3\text{-}3).$$

The first exponential is the median interference range to communication range ratio and the last factor (including the variable attenuation) is a random multiplier.

As an example, assume α = 3 and Γ_i = 13 dB and equal power levels in each system. The median interference range is then 2.7 times the communication range. The mean transmission distance to the center of a centralized LAN cell is 0.75 times the cell radius. Thus, the median interference distance is approximately 2.7x0.75 = 2.0 times the cell radius and the median interference area is approximately 4 times the communication coverage area.

The effect of power level can better be illustrated by computing the proportion of WBFH devices in a typical deployment area that create interference to a victim transmitter-receiver combination. The victim system might be a wireless LAN system, but it may also be another type of packet based digital communication system.

Consider the region outlined in figure 3-2. Here potential victim devices and potentially interfering WBFH devices are evenly distributed over the area of radius r_t. The victim devices operate in a centralized mode in which all transmissions involve a centralized access point (a in the diagram) and a mobile device (m in the diagram). The inner concentric circle of radius 1 is the boundary of the victim system cell, that is, the victim devices within this circle communicate through the access point shown. A rectangular deployment area is more typical, but a circular deployment area and cell shape lends itself to a convenient evaluation and will serve to show the power level effect.

Building or office area size normally establishes the deployment area dimensions. Usually, a single cell will be sufficient to cover an area; a power level of 50 mW is sufficient to reliably cover a communication radius of up to 50 meters. The single cell deployment area case is represented by r_t = 1.

Figure 3-2 illustrates the following development.

Establish the proportion of interfering devices at a distance r_i from the mobile receiver (those within a small differential of the dotted line in figure 3-2). The receiver is a distance c from the desired transmitter. To do this rearrange equation 3-2 as follows.

$$A_{v1} - A_{v2} = A_{vt} = P_{21} - P_2 + \Gamma_i - 10\alpha Log\left(\frac{r_i}{c}\right)$$

This gives the necessary deviation from the mean of the two distance attenuation values to make the interference distance equal r_i when the communication distance is c.

A_{v1} and A_{v2} are the fading and shadowing variation in attenuation. A_{v1} and A_{v2} are each approximately normally distributed with mean zero. The variance difference is the sum of the variances of each and the standard deviation is the square root of the variance.

Let the standard deviation of $A_{vt} = A_{v1} - A_{v2}$ be A_s. Then A_{vt}/A_s is a random variable of mean zero and standard deviation 1.

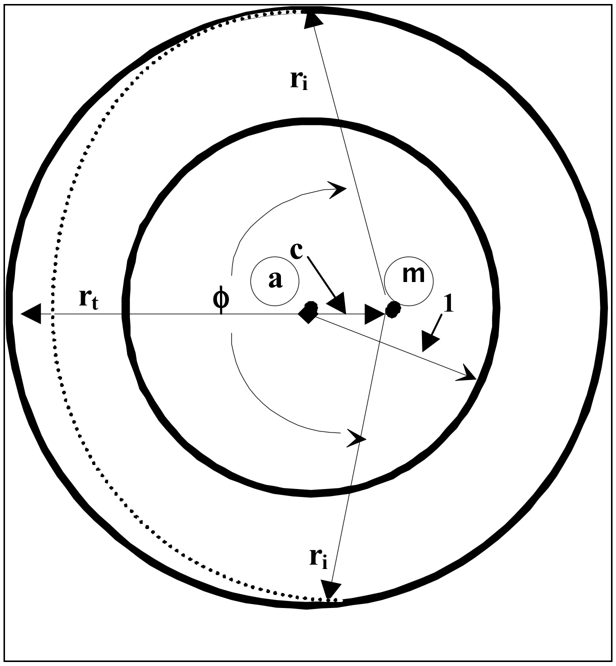


Figure 3-2. Configuration for Analyzing the Relative Number of WBFH Interferers.
The mobile device (m) is receiving from the access point (a). The inner concentric circle is a centralized LAN cell for which the radius is normalized to 1. The deployment area is defined by the outer circle of normalized radius r_t. The normalized communication distance is c. The dotted line is a circular arc of radius r_i on which all WBFH devices are equidistant from the mobile receiver. Interfering and victim devices are evenly distributed within the area.

If the interferer bandwidth is greater than the victim bandwidth, the interferer power received by the victim is reduced by the bandwidth ratio factor β.

$$\beta = 10Log\left(\frac{B_h}{B_i}\right) \quad B_h > B_i$$

$$\beta = 0 \quad otherwise.$$

Then $P_{21} = P_2 - \beta$ and

$P_2 - P_1 = \Delta P$.

Using the above definitions, equation 3-2 can be rearranged to

$$\frac{A_{vt}}{A_s} = \frac{\Delta P - \beta + \Gamma_i}{A_s} - \frac{10\alpha}{A_s} Log\left(\frac{r_i}{c}\right).$$

The random variable A_{vt}/A_s has a mean of zero and a standard deviation of 1 and approximately obeys the normal probability distribution.

Define X as the right hand side of the equation

$$X = \frac{\Delta P - \beta + \Gamma_i}{A_s} - \frac{10\alpha}{A_s} Log\left(\frac{r_i}{c}\right). \qquad (3\text{-}4)$$

Let $P_n(X)$ be the value of the normal distribution function for a variable of mean zero and standard deviation 1, then

$$P_n(X) = \Pr\left(\frac{A_{vt}}{A_s} > X\right)$$

equals the probability that a WBFH device at distance r_i will interfere when the victim communication distance is c. In other words, $P_n(X)$ is the proportion of devices at distance r_i which will have sufficient power level to interfere with the victim device when the communication distance is c.

If N_h is the total number of WBFH devices within the deployment area (the area bounded by r_t in figure 3-2), then the density of WBFH devices is $N_h / \pi r_t^2$. If these devices are evenly distributed, the number of devices within δr_i of the dotted arc in figure 3-2 is $N_h / \pi r_t^2 \left(\phi r_i \delta r_i\right)$.

Further, the number which interfere with the mobile receiver (ΔN_m) is

$$\Delta N_m = \frac{N_h}{\pi r_t^2} \phi\left(r_{i,} c\right) r_i P_n\left(r_{i,} c, \Delta P, \beta, \Gamma_i\right) \delta r_i \qquad (3\text{-}5)$$

The angle of the arc in figure 3-2 (ϕ) can be established to be

$$\begin{aligned} \phi &= 2Cos^{-1}\left(\frac{r_i^2 - r_t^2 + c^2}{2 r_i c}\right) \quad r_i \geq r_t - c \\ \phi &= 2\pi \qquad r_i < r_t - c \end{aligned} \qquad (3\text{-}6)$$

Thus, the integral of equation 3-5 from 0 to r_t+c is the total number of WBFH devices that interfere with the mobile receiver when the communication distance is c.

When the LAN receiver is at the access point the number of devices that interfere is defined as N_a. In this case, ϕ is always 2π and the number of devices that interfere with the access point receiver is the integral of equation 3-5 from 0 to r_t with ϕ always equal to 2π.

The communication distance within the cell (c) is also a random variable and the number of interferers must be weighted by the probability density of c. This probability density is

$$\frac{p(x)}{\delta x} = \Pr\left(x - \delta x/2 < c < x + \delta x/2\right) = 3x^2$$

The overall proportion of devices that interfere is determined by the double integral

$$N_x = 3\int_c c^2 \int_{r_i} \Delta N_x\left(r_i, c, etc\right) \qquad (3\text{-}7)$$

where x is either a or m.

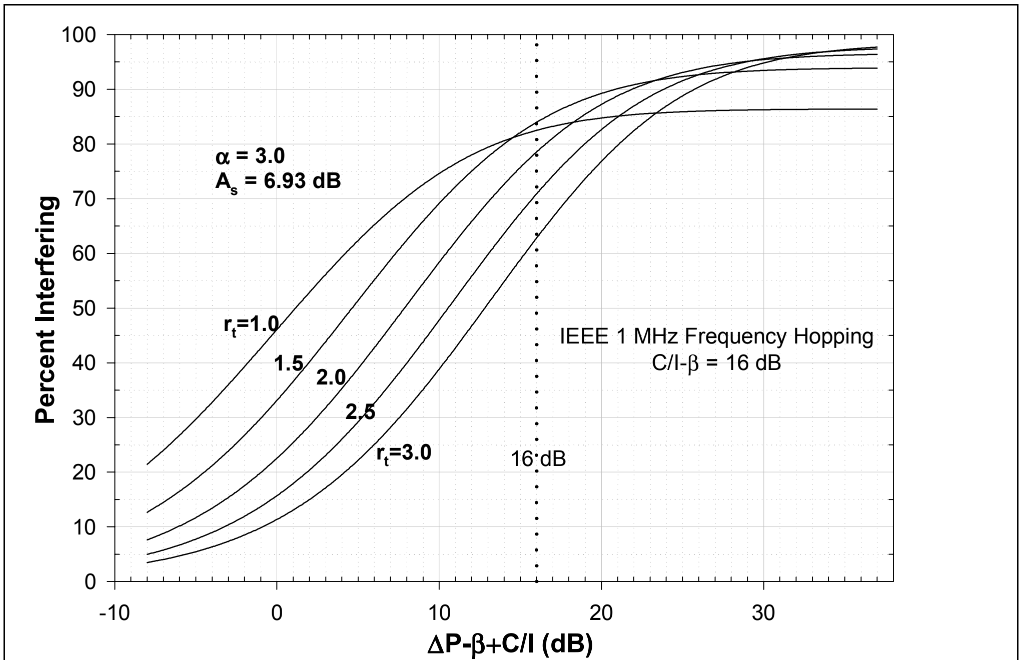
Annex 1 gives the full equations and description of the numerical integration used.

In a typical centralized wireless LAN, such as an IEEE 802.11 standard LAN operating through an access point, the information flow is balanced to and from the access point. Some packets must flow in the opposite direction to the information flow, but these are supervisory packets and are of shorter duration than the information packet. The overall proportion of WBFH transmitters that interfere will be slightly higher because of the supervisory packet flow, however this increase will be small and it will be assumed here that the overall proportion is $(N_a + N_m)/2N_h$.

A graph of this quantity versus the power level related parameters is given in figure 3-3.

The parameters of the graph are typical values that can be expected in a relatively open office type environment. The propagation exponent α is typically about 3 in such an environment and this is used in the graph.

The attenuation variation about the regression value predicted by the exponent α is comprised of a variation due to shadowing and another due to multi-path fading. The typical variation due to shadowing is 3 to 4 dB and that due to fading is about the same. The fading component can be made negligible in the desired communication path by equalization and diversity techniques. So, a reasonable value of the overall standard deviation of the difference attenuation A_s can be derived by assuming three 4 dB components which add in an RMS manner. The value of 6.93 dB used in the graph is 4 times the square root of 3.



Proportion Interfering Vs. Differential Power Level

Figure 3-3.

This shows the quantity $(N_a + N_m)/2N_h$ for various ratios of deployment radius to cell radius. Typical values of the parameters α and A_s are used. The vertical dotted line at 16 dB corresponds to the case where an IEEE p802.11 standard frequency hopping wireless LAN victim system has the same power level as the interfering WBFH system.

The curves of figure 3-3 tend to become flat as the C/I requirement of the victim receiver increases. High C/I requirements are characteristic of systems with high modulation efficiency. Thus, the interference effect due to power level difference is relatively insensitive to reducing the interferer power level in high modulation efficiency devices.

4.0 Composite Interference Effect

The probability of packet overlap of a wide bandwidth frequency hopping system on a packet data system was developed in section 2 on the assumption of a fixed population of interfering transmitters all of which had sufficient power level to create interference. Section 3 then shows the effect of power level and bandwidth on the size of this population.

The overall packet interference probability can be considered to be the product of three factors

1. A factor dependent on the hopping frequency or period.
   This is the $(H_t+P_t)/H_t$ term of equation 2-1.
2. A factor dependent on the relative bandwidths.
   This is the $B_{ih}/Bt \approx (Bh+Bi)/Bt$ term of equation 2-1.
3. A factor dependent on the interference to victim power level ratio.

Equation 2-1 of section 2 gives the packet overlap probability (λ) dependence on the WBFH frequency hopping rate and bandwidth.

$$\lambda = Mp\left[\frac{H_t + P_t}{H_t}\right]\left[\frac{B_{ih}}{B_t}\right]$$ and section 3 added the effect of power level.

<u>The Hopping Frequency Factor</u>

This is the factor $\frac{H_t + P_t}{H_t}$ of equation 2-1. This term increases with the hopping rate ($1/H_t$) of the interfering frequency hopper. Increasing the bandwidth as proposed for the WBFH permits the hop time (H_t) to be lowered and thus permits a higher interference factor.

The fastest hopping time is likely to be the amount of time necessary to transfer one packet of information. This will usually include an exchange of a long information packet and one or more short supervisory packets. The victim will be susceptible to interference on each packet transferred; if either packet is mutilated the information packet will need to be retransmitted.

Consider the time for the complete packet exchange associated with one information packet to be the packet time. It is reasonable to assume that the frequency hopper will hop as fast as practical and this is after each of its information packet exchanges[2]. In this case, the hop time is the packet time of the frequency hopper. It is also reasonable to consider that both the hop time and the packet time is inversely proportional to the signaling speed. If each system uses packets containing the same amount of information (the same number of bits), then each would have a packet time bearing the same inverse proportionality to signaling rate.

Thus,

$\frac{H_t + P_t}{H_t} = \frac{k/S_{ri} = k/k/S_{ri}}{k/S_{ri}} = 1 + \frac{S_{ri}}{S_{rv}}$. S_{ri} and S_{rv} are the signaling rate of the interferer and victim systems respectively.

The IEEE p802.11 frequency hoping LAN has an upper signaling speed of 2 MB/s. This is two times the 20 dB bandwidth, thus it will be assumed that the signaling speed of a frequency hopper is $2B_h$ where B_h is the 20 dB bandwidth as in section 2.

The ratio of this factor with a hopping bandwidth of B_h to that when the bandwidth is 1 MHz is then

$$\text{Hopping rate factor} = \frac{S_{rv} + 2B_h}{S_{rv} + 2}.$$

Table 4-1 gives values of this factor for the current signaling speeds of the IEEE p802.11 standard.

[2] The IEEE p802.11 frequency hopping hop time is 100 milliseconds. This makes the hopping rate factor negligible and makes the standard frequency hopper friendlier to both other frequency hoppers and to direct sequence systems.

Victim signaling speed S_v (Mb/s)	Frequency hopper bandwidth (B_h in MHz)	Hopping rate factor
any	1	1
1	3	2.33
2	3	2
5.5	3	1.53
11	3	1.42
1	5	3.67
2	5	3.00
5.5	5	2.07
11	5	1.75

Table 4-1: Values of the Hopping Rate Factor in Interference Probability
The interference probability of a frequency hopping system is increased by this factor if the frequency hopping bandwidth is increased from 1 MHz to B_h, the frequency-hopping period is equal to an information packet transmission time and all packets contain the same amount of information.

Even at the highest signaling speeds now used, the hopping rate factor is very significant.

The Hopping Bandwidth Factor

This is the factor $\frac{B_{ih}}{B_t} \approx \frac{B_i + B_h}{B_t}$ of equation 2-1. The current frequency hopping bandwidth is 1 MHz and the total hopping band (B_t) is proposed to stay the same for the WBFH. Thus, the ratio of the value of this term with a wideband frequency hopping system to the value with a 1 MHz bandwidth frequency hopping system is

$$\text{Bandwidth factor} = \frac{B_i + B_h}{B_i + 1}.$$

Table 4-2 compares this factor for the two bandwidths used in the IEEE p802.11 standard. The frequency hopping PHYsical layer (PHY), 20 MHz bandwidth is 1 MHz and the direct sequence PHY bandwidth is approximately 17 MHz.

Victim bandwidth (B_i)	Frequency hopping bandwidth (B_h)	Bandwidth factor
any	1	1
any	1	1
1	3	2.00
1	5	3.00
17	3	1.11
17	5	1.22

Table 4-2: Values of the Bandwidth Factor in Interference Probability
The interference probability of a frequency hopping system is increased by this factor if the frequency hopping bandwidth is increased from 1 MHz to B_h.

5.0 WBFH Interference to IEEE p802.11 Standard LANs

Wireless packet data systems conforming to the IEEE p802.11 standard for wireless LANs will be used as example systems to demonstrate the relative interference potential of wide bandwidth frequency hopping systems. The IEEE p802.11 standard specifies both a frequency hopping and a direct sequence spread spectrum wireless LAN PHYsical layer (PHY) using the 2.4 GHz band. Most systems now in operation follow this standard.

The IEEE direct sequence PHY uses a chip rate of 11 Mchips/second. The 20 dB bandwidth is not specified but is usually about 17 MHz. The direct sequence signaling speeds are 1, 2, 5.5 and 11 Mb/s. The frequency hopping PHY uses a 20 dB bandwidth of 1 MHz and signaling speeds of 1 and 2 Mb/s.

The IEEE p802.11 wireless LAN products now typically use a power level of about 16 to 20 dBm even though the permissible level is 30 dBm. The lower power level is easier to generate and is sufficient for the inside communication distances for which the LANs are used. The petitioners seeking to increase the frequency hopping bandwidth propose to limit the WBFH power level to 23 and 25 dBm. Since this is above the levels now used, it will have likely have little effect on the WBFH power level. It can be expected that WBFH LANs will have about the same power level as current LANs if the power level limit is lowered.

This section evaluates the overall interference effect caused by increasing the frequency hopping bandwidth, taking into account the two factors of section 4 and the power level effect of section 3.

It can be expected that the most severe effect will be on 1 MHz bandwidth frequency hopping systems as opposed to that on the direct sequence systems. This is because the direct sequence systems have higher bandwidth and signaling speed and are more resistant to interference, that is, the interference distance of section 3 is lower.

Direct sequence spread spectrum systems are necessary, within the current rules, if signaling speeds above about 2 Mb/s are required.

Direct sequence systems are very sensitive to fast frequency hopping systems. The IEEE p802.11 standard uses slow frequency hopping which neutralizes the hopping rate factor between the IEEE p802.11 systems and thus makes the standard systems more compatible.

The hopping rate factor of table 4-1 is compared to a 1 MHz bandwidth system that also uses fast frequency hopping. The ratio would be much higher if a fast frequency hopping WBFH system was compared to the slow hopping system of IEEE p802.11.

<u>IEEE p802.11 Frequency Hopping System</u>

Widening the bandwidth without changing the interferer power level reduces the interference power level within a 1 MHz bandwidth frequency hopping receiver, thus β of section 3 is greater than 1 for a 1 MHz bandwidth frequency hopping victim. This power reduction factor (β) for the proposed interfering system bandwidths is

β = 0 dB for the 1 MHz bandwidth,

β = 4.8 dB for the 3 MHz bandwidth and

β = 7 dB for 5 MHz bandwidth.

The IEEE standard frequency hopping LAN C/N requirement is 23 dB for 2 Mb/s and 20 dB for 1 Mb/s and the wide bandwidth signals intercepted by a narrow bandwidth receiver can be treated as gaussian noise. Thus, the C/I (Γ_i of the equations) requirement is approximately the same as the C/N requirement.

The probability of packet overlap is directly proportional to the bandwidth factor of table 4-2 times the hopping rate factor of table 4-1. The approximate value of the bandwidth factor for 3 and 5 MHz bandwidth systems compared to 1 MHz bandwidth systems is 2 and 3 respectively (table 4-2). The factor due to the potentially higher hopping rate can also be 2 or 3 respectively (table 4-1).

As an example, assume that the WBFH bandwidth is 5 MHz and the product of these factors is 3. This is the minimum value of the factor and would apply if the WBFH hop time effect was negligible due to a low hopping rate.

Refer to figure 3-3 to assess the power level effect.

For a total area equal to one communication cell (r_t = 1), 85.6 percent of the 1 MHz frequency hoppers will have high enough power level to interfere with the 2 Mb/s IEEE LAN (∇P = 0, β = 0 and C/I = 23 dB). 82.5 percent of the 5 MHz frequency hoppers will interfere (∇P = 0, β = 7 dB and C/I = 23 dB). Thus, the reduction in the proportion that interfere due to the reduced level of intercepted power is 82.5/85.6 = 0.96, provided the systems use the same power level.

However, three times as many devices of equal power level generate overlapping transmissions when the bandwidth is increased to 5 MHz. The proportion of devices with sufficient power level to interfere would need to be reduced to 1/3 to compensate. That is, the proportion interfering would need to be no more than 85.6%/3 = 28.5%. This would require a 21.0 dB power reduction in the 5 MHz frequency hopper transmitter relative to the 1 MHz system power level.

If the power level difference is 7 dB (as required by the proposed rules if all systems operate at maximum permissible power), the proportion of interferers becomes 72.6%. Thus, an increase of the bandwidth to 5 MHz accompanied by a 7 dB power reduction increases the number of interferers by at least a factor of 72.6x3/85.6 = 2.5.

Table 5-1 shows the shows the result of the above computation for a range of bandwidth and interference factors. The table shows the amount the WBFH power would have to be reduced relative to the 1 MHz bandwidth system power in order to maintain the same interference probability for the 3 and 5 MHz bandwidth systems as for a 1 MHz bandwidth system. The bandwidth-hopping rate factor applies to a 1 MHz bandwidth device with a C/I value of 23 dB. The bandwidth – hopping rate factor (column 3) is shown at an intermediate and a maximum value for each WBFH bandwidth.

The proportion of devices with sufficient power level to interfere decreases with larger deployment areas. However, even at very large deployment areas the increased bandwidth causes increased interference unless the power level of the WBFH systems is drastically lower than that of the 1 MHz bandwidth systems.

Total radius to cell radius ratio (r_t)	Bandwidth ratio power reduction factor β (WBFH bandwidth)	Product of bandwidth and hopping rate factors	Necessary WBFH power reduction
1.0	4.8 dB (3 MHz)	2	19.0 dB
1.0	"	4	> 26 dB
1.0	7 dB (5 MHz)	3	21.0 dB
1.0	"	9	> 26 dB
1.5	4.8 dB (3 MHz)	2	14.5 dB
1.5	"	4	21.5 dB
1.5	7 dB (5 MHz)	3	13.5 dB
1.5	"	9	> 24 dB
2.0	4.8 dB (3 MHz)	2	11.5 dB
2.0	"	4	18.0 dB
2.0	7 dB (5 MHz)	3	13.5 dB
2.0	"	9	22.0 dB

Table 5-1: Necessary Power Level Difference to Equalize Interference Probability to a 1 MHz Bandwidth 2 Mb/s System.

The interference probability of a frequency hopping system of 3 and 5 MHz bandwidth is compared to that of a 1 MHz bandwidth system. The wider bandwidth system power level would need to be less than that of a 1 MHz bandwidth frequency hopping system by the amounts of the table if the interference potential is to be equalized. The victim system has a 1 MHz bandwidth and a 23 dB C/I requirement. These parameters approximately match the IEEE p802.11 2 Mb/s frequency hopping PHY.

Direct Sequence System

The IEEE p802.11 direct sequence PHY uses an 11 Mchip/second signaling rate and has a 20 dB bandwidth of approximately 17 MHz. Thus, the bandwidth factor affecting the number of overlapping transmissions is 1.11 and 1.22 for the 3 MHz and 5 MHz WBFH systems respectively (table 4-2) and the hopping rate factor is potentially 1.42 and 1.75 respectively. Thus, the potential bandwidth – hopping rate factor product is 1.6 for the 3 MHz bandwidth and 2.1 for the 5 MHz bandwidth.

A typical 11 Mb/s IEEE p802.11 direct sequence implementation has a C/N requirement of 12.5 dB and a C/I requirement for a single frequency tone of about 7 dB. When a constant amplitude interfering signal has a bandwidth in excess of that of the unspread direct sequence signal, the C/I requirement is higher than for a narrower bandwidth signal. Thus, the C/I requirement for a 1, 3 and 5 MHz bandwidth constant amplitude modulated signal is between 7 dB and 12.5 dB if the interfering signal is of constant amplitude. The requirement increases with increasing bandwidth.

There is no assurance that the WBFH system will use a constant amplitude signal. If the signal is not constant amplitude, the C/I requirement could be as high as the C/N requirement of 12.5 dB.

A C/I requirement of 10 dB will be assumed for comparison purposes. The interference effect would be worse if the WBFH signal is not of constant amplitude.

Table 5-2 shows the shows the amount the WBFH power would have to be reduced relative to that of a direct sequence system power in order to maintain the same interference probability for the 3 and 5 MHz bandwidth systems as for a 1 MHz bandwidth system. The bandwidth-hopping rate factor applies to device such as an IEEE p802.11 standard direct sequence PHYsical layer (PHY) with a bandwidth of 17 MHz, a signaling speed of 11 Mb/s and a C/I requirement of 10 dB.

Total radius to cell radius ratio (r_t)	Product of bandwidth and hopping rate factors	Necessary WBFH power reduction
1.0	1.6	10
1.0	2.1	13
1.5	1.6	7.0
1.5	2.1	10
2.0	1.6	9.0
2.0	2.1	8.5

Table 5-2: Necessary Power Level Difference to Equalize Interference Probability to a Direct Sequence Spread System.

The interference probability of a frequency hopping system of 3 and 5 MHz bandwidth is compared to that of a 1 MHz bandwidth system in which the victim system is a direct sequence spread spectrum system of 17 MHz bandwidth and 11 Mb/s signaling speed. The wide bandwidth frequency hopping system power level would need to be less than that of a 1 MHz bandwidth frequency hopping system by the amounts of the table if the interference potential is to be equalized. The victim system has a 10 dB C/I requirement. These parameters approximately match the IEEE p802.11 11 Mb/s direct sequence PHY.

The table does not take into account the effect of the higher C/I needed for wider bandwidth interferers. This effect is likely on the order of 1 to 3 dB. Thus, the overall effect is 14 to 16 dB on a direct sequence packet data system with the parameters used in the table. Other direct sequence systems may use lower bandwidth and higher C/I. The effect would be worse on such systems.

An increased bandwidth for a direct sequence system would harm the interference susceptibility from all frequency hopping systems; increasing the direct sequence bandwidth with higher spreading would not be of benefit. this would aid in the relative performance but worsen the overall performance.

Conclusions of Section 5

The specific systems evaluated serve to illustrate the effect of a wider frequency hopping bandwidth on a range of current packet data systems. The effect of increasing the frequency hopping bandwidth is most severe on the 1 MHz bandwidth frequency hopping packed data system because of the low bandwidth and the high C/I ratio. It is less on the direct sequence system because the bandwidth is higher and the C/I is lower for this system.

These specific systems are critical however. IEEE p802.11 has spent 8 years establishing these standards based on the current spread spectrum rules.

6.0 Summary and Conclusions

The effect of the frequency hopping spread spectrum bandwidth and hopping rate on interference generation was first analyzed separately form power level, then the effect of power level was investigated.

A particular physical configuration including a WBFH system and a potential victim system in a common area was analyzed for the influence of power level on interference. The necessary reduction in power level of a wide bandwidth frequency hopping system compared to a system following the current rule in order to maintain equal interference probability was evaluated.

Lowering the regulation limits by 5 to 7 dB for wider bandwidth frequency hopping, as proposed, will not ensure any relative power level reduction on current systems. Current spread spectrum wireless LANs utilize power levels 10 to 13 dB below the allowable limits. This is all that is necessary to operate at the normal inside ranges and propagation conditions now encountered. The regulations would need to lower the limits by at least 10 dB in addition to the values determined here in order to assure the interference potential of the wide bandwidth systems is not higher than that of the current rules.

It was shown that the interference potential increases with the frequency hopping rate as well as bandwidth; and a higher bandwidth permits a faster hopping rate. An upper limit on the frequency hopping rate would be better than a lower limit. The proper upper limit would lower the interference potential of 1 MHz bandwidth systems as well as that of higher bandwidth systems.

Lowering power has little effect on systems with high modulation efficiency. Such systems have a high C/I requirement and the median interference range exceeds most deployment area sizes.

Increasing the frequency hopping bandwidth to 3 or 5 MHz, as proposed, was shown to have a very severe effect on low bandwidth systems with a high C/I requirement such as systems conforming to the current frequency hoping rules. A packet data system conforming to the IEEE p802.11 frequency hopping standard was used as the example of such a system. The necessary power level reduction for this system with slow frequency hopping is on the order of 20 dB compared to a 1 MHz frequency hopping system. It is in excess of 26 dB for fast frequency hopping.

The effect on a typical direct sequence system was also evaluated. This was shown to be about 13 to 16 dB. Most of this effect is due to the potential effect of fast frequency hopping. There is a severe effect on direct sequence systems from any fast frequency hopping system. IEEE p802.11 alleviates this effect by requiring slow frequency hopping in the standard frequency hopping PHY.

Interference from any frequency hopping system to a direct sequence system increases with increasing direct sequence bandwidth, even though relative interference of wide bandwidth systems and 1 MHz bandwidth systems decreases with frequency hopping bandwidth. Thus, increasing the spreading gain is not a reasonable option for lowering the interference effect.

References

1. Effect of Overlapping Channels on WBFH Systems Reliability. Jim Zyren, Don Sloan and Ad Kamerman, doc.: IEEE p802.11-99/170, July, 1999.

Annex 1 : Evaluation of the Relative Numbers of Interferers

This section shows the detailed equations used to evaluate the proportion of WBFH devices that interfere as a function of the power level, bandwidth and victim receiver parameters. The parameters below are defined in the main text.

The quantity $P_n(X)$ is common to the equations for both the mobile and the access point victim devices in a centralized LAN cell. In each case

$$X = \frac{\Delta P - \beta + \Gamma_i}{A_s} - \frac{10\alpha}{A_s} Log\left(\frac{r_i}{c}\right) \text{ and}$$

$P_n(X)$ is the normal probability distribution function for a mean of zero and standard deviation of 1.

The proportion of WBFH devices that interfere with the <u>mobile</u> device was evaluated using the following summation.

$$\frac{N_m}{N_h} = \frac{3}{\pi r_t^2 N_{mx} M_{mx}} \sum_{n=1}^{N_{mx}} (c)^2 \sum_{m=1}^{M_{mx}} (r_i)(r_i + c)\phi(r_i, c) P_n(X) \qquad \text{(A1)}$$

in which

$$r_i = \frac{m - .5}{M_{mx}}(r_t + c),$$

$$c = \frac{n - .5}{N_{mx}} \text{ and}$$

$$\phi = 2Cos^{-1}\left(\frac{r_i^2 - r_t^2 + c^2}{2 r_i c}\right) \quad r_i \geq r_t - c \; .$$

$$\phi = 2\pi \qquad r_i < r_t - c$$

N_{mx} and M_{mx} determine the number of steps used in the numerical integration. Computations compared within 1% with N_{mx}, M_{mx} = 10 and 25. N_{mx}, M_{mx} = 25 was used in the evaluation.

The proportion of WBFH devices that interfere with the <u>access point</u> was evaluated using the summation.

$$\frac{N_a}{N_h} = \frac{6}{r_t^2 N_{mx} M_{mx}} \sum_{n=1}^{N_{mx}} (c)^2 \sum_{m=1}^{M_{mx}} r_i r_t P_n(X) \qquad \text{(A2)}$$

in which

$$r_i = \frac{m-.5}{M_{mx}} r_t$$

$$c = \frac{n-.5}{N_{mx}}$$

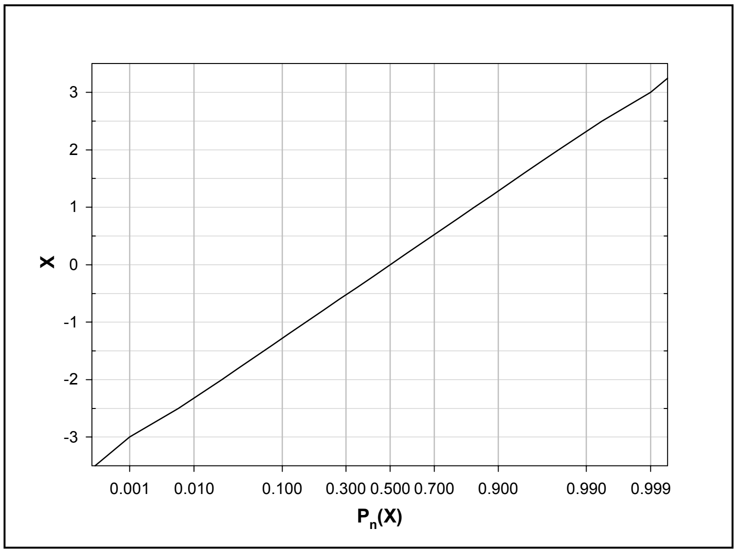
Equation A2 differs from equation A1 in the definition of r_i and the fact that ϕ is a constant equal to 2π radians for the access point.

The table below was used to determine $P_n(X)$. Linear interpolation was used between the points of the table.

X	$P_n(X)$
0	.500
.2	.579
.4	.655
.6	.726
.8	.788
1	.841
1.2	.885
1.4	.919
1.6	.945
1.8	.964
2	.977
2.5	.994
3	.999
3.5	1.000

$P_n(-X) = 1-P_n(X)$

$P_n(X) = 1$ for X >= 3.5.



Annex 2

Effects of WBFH Power Reduction and Hop Rate

Date: September 13, 1999

Author: Jim Zyren and Pierre Gandolfo
Intersil
Melbourne, Florida, USA
Phone: (407)729-4177
Fax: (407)724-7886
e-Mail: jzyren@intersil.com, pgandolf@intersil.com

Abstract

In a recent NPRM (ET Docket 99-231), the FCC proposed to amend the rules for Frequency Hopping Spread Spectrum (FHSS) radios operating in the 2.45 GHz ISM band. Proposed rule changes include reduced transmit power levels and faster hop rates for Wide Band Frequency Hopping (WBFH) radios operating on 3 MHz or 5 MHz wide channels. The impact of proposed power reductions is discussed. An analysis demonstrating that increasing the required minimum hop rate for WBFH radios actually increases interference to other users is presented.

1.0 Summary

Intersil opposes changes in the operating rules governing operation of FHSS radios in the 2.45 GHz band as proposed by the HomeRF Working Group in a November, 1998 petition for rule making. In that petition, HomeRF sought an increase in the FHSS occupied channel width. This increase would allow FHSS radios to operate with channel widths of 1, 3, or 5 MHz. Systems employing 3 MHz wide channels or 5 MHz wide channels are collectively referred to as Wide Band Frequency Hopping (WBFH) radios.

HomeRF asserted that the interference resulting from the wider channel widths could be offset by a combination of power reduction in proportion with the expansion in channel width, and an increase in the hop rate. The rules for the three variations of FHSS channel width are summarized in Table 1.0-1.

Channel Width	Max Power	Max Dwell Time	Minimum # Hops
1 MHz	30 dBm	400 msec	75
3 MHz	25 dBm	50 msec	75
5 MHz	23 dBm	20 msec	75

Table 1.0-1 Proposed FHSS Channel Parameters

In the subsequent NPRM (ET Docket 99-231), the Office of Engineering and Technology (OET) indicated that it was of the opinion that the proposed rule changes would not result in increased interference to Direct Sequence Spread Spectrum (DSSS) systems. However, OET specifically sought comment on whether the reduction in power and increase in hop rate as described above would, in fact, preclude any increase in interference to DSSS systems.

Due to the fact that nearly all portable FHSS and DSSS radios operating in accordance with Part 15, Section 247 of the Commission's Rules transmit at 20 dBm (100 mW) or less, the power reductions suggested by HomeRF appear to offer little or no protection to existing users of the 2.45 GHz ISM band. In addition, it is shown by simple analysis that increasing the hop rate as suggested by HomeRF will actually result in an increase in interference to existing DSSS and FHSS systems.

2.0 Power Reduction

The reduction in power as proposed by HomeRF is not adequate to ensure that existing users of the band, including both FHSS and DSSS radios, will not suffer adverse effects. The reason is simple. The reduced power levels shown in Table 1.0-1 are above the transmit power levels of nearly all portable devices on the market today.

The vast majority of IEEE 802.11 WLAN devices transmit at 100 mw (+20 dBm) or less. Most Bluetooth devices will radiate at only 1 mW (0 dBm).

These systems use transmit power levels far below the limit permitted under Section 15.247 of the Commission's Rules in order to maximize battery life in portable computing devices. Technologies such as Bluetooth and IEEE 802.11 WLANs are intended to facilitate wireless mobile computing. Battery life is therefore a paramount consideration in these types of devices.

Based on HomeRF's presentation to the FCC on Feb. 25, 1999 [1] it is clear that the intended modulation scheme is 4FSK. Delivery of 10 Mbps data rates using this form of modulation in a 5 MHz wide channel will require a very low index of modulation index (h) of about 0.15. This is an extremely inefficient modulation technique as demonstrated by the Eb/No curves shown in Figure 2.0-1.

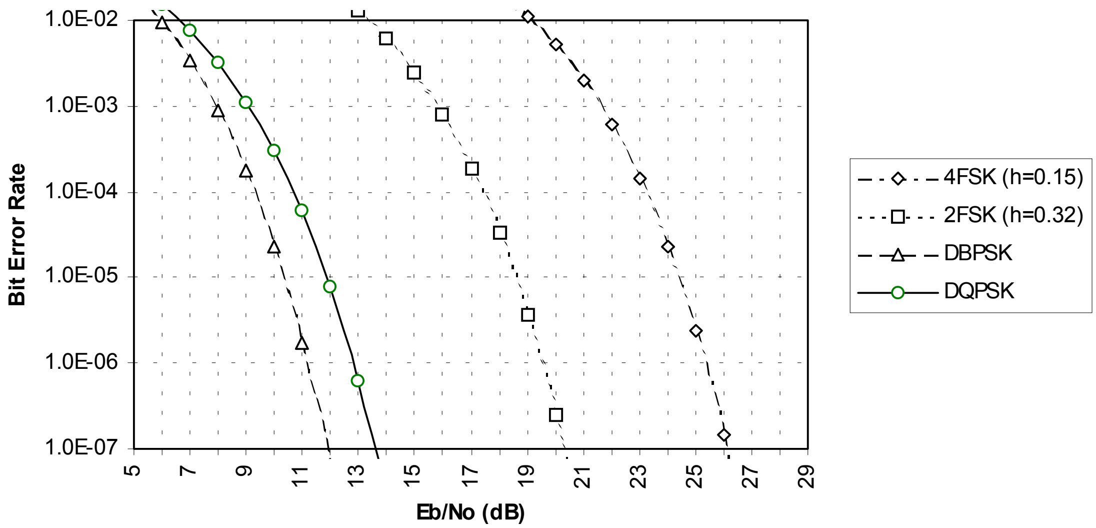


Figure 2.0-1 Eb/No vs. BER for FSK and PSK Waveforms

In addition, the 4FSK waveform is also highly susceptible to multipath. Due to the inefficiency of the 4 FSK waveform and susceptibility to multipath, WBFH radios will be required to operate at or near the maximum allowable transmit power (+23 dBm). Even at this power level, it is doubtful that a WBFH system as proposed by HomeRF could provide a Quality of Service (QoS) adequate to support the types of multimedia applications described in their letter to the Commission of November 11, 1998.

2.1 Previous Rulings

The power reductions proposed by HomeRF are linear in relation to the increase in channel width. In a previous ruling on a similar proposal by Symbol (FCC 96-36), the Commission commented on the potential interference to both authorized services and other Part 15 devices:

"While this increase in interference potential could be partially offset by a reduction in the output power of the frequency hopping transmitters, we are not convinced that a linear power reduction alone is sufficient to offset this interference potential."

The Symbol proposal differed from the HomeRF proposal in that it called for a decrease in the number of FHSS hopping channels in proportion to the increase in channel width. In this sense, the Symbol proposal was technically superior to the HomeRF proposal. The use of overlapping channels will actually increase the collision rate among WBFH systems, and in no way reduces interference to other Part 15 devices.

In a proceeding relating to the reduction of the number of channels in the 915 MHz band (FCC 97-147), the Commission granted the request to reduce the number of hopping channels to allow FHSS systems operating in that band to avoid interfering with other services. However, the Commission recognized that such a reduction hopping channels would result in an increase in collisions among FHSS systems in the 915 MHz band.

In order to offset the potential for increased interference, the Commission adopted rules which required systems using fewer hopping channels to reduce power *in proportion to the square of the reduction in the number of hopping channels.* This conclusion was based on comments submitted by TIA Wireless[2]. In the 915 MHz ISM band, systems using 50 hopping channels are permitted to transmit at up to 1 Watt, while systems using fewer channels (but not fewer than 25) are limited to 250 mW.

The use of overlapping channels obscures this issue to some extent. However, in a previous submission to OET in this proceeding [3], the adverse impact of allowing overlapping FHSS channels has been demonstrated. The number of overlapping FHSS channels is largely irrelevant. Collision rates among FHSS systems can be reduced only by increasing the number of *orthogonal* (non-overlapping) channels. In this sense, the HomeRF proposal contains the same number of orthogonal channels as the earlier proposal by Symbol. It should therefore become more apparent that the linear power reduction proposed by HomeRF is inadequate to offset the increased potential for interference to other users of the 2.45 GHz band.

3.0 Hop Rate

In its letter to the Commission of Nov. 11, 1999, HomeRF indicated that the reduction in time of occupancy is an effective means of reducing interference between WBFH and other users of the spectrum. It must be pointed out that a reduction in occupancy time requires a corresponding increase in hop rate. However, even neglecting the expansion in bandwidth, when averaged over a 30 second period the time of occupancy on any single channel is unchanged. The net result of the proposed increase in hop rate is therefore more frequent collisions of a shorter duration.

Increasing the hop rate of an FHSS system is *NOT* a means of reducing interference with either DSSS or other FHSS systems. In fact, increasing the hop rate for an FHSS system *increases* the risk of interference to other users. A model for predicting the collision rate with an FHSS system has been proposed [4]. The model can be used to determine the rate of collision between a DSSS system and an FHSS system, or between two FHSS systems.

In the event of a collision, any bit error will cause the Cyclic Redundancy Code (CRC) of a packet transmission to fail, and the packet will be lost. The model estimates the probability of collision based on:

1.) Hop rate of the interfering signal (HR)
2.) Probability that FHSS interfering signal hops into passband of desired signal (P_{hop})
3.) Probability that FHSS system actively transmits while on any given hop (P_{tx})
4.) Packet length (in time) of desired signal transmission (L_{packet})

The effect of hop rate can be shown by studying the example of a DSSS system operating at 1 Mbps in the presence of a nearby FHSS system. The bandwidth of a DS signal is roughly 20 MHz. Therefore the probability that the FHSS system will hop into the DSSS passband is 20/79, or about 25%. In this example, all parameters are held constant with the exception of hop rate. In the first case, the FHSS system is 128 hops per sec, which results in an FHSS dwell period (t_{dwell}) on any given channel of 7812 usec.

Case 1:

HR	=	128 hops/sec
P_{hop}	=	25%
P_{tx}	=	100 %
L_{packet}	=	8370 usec

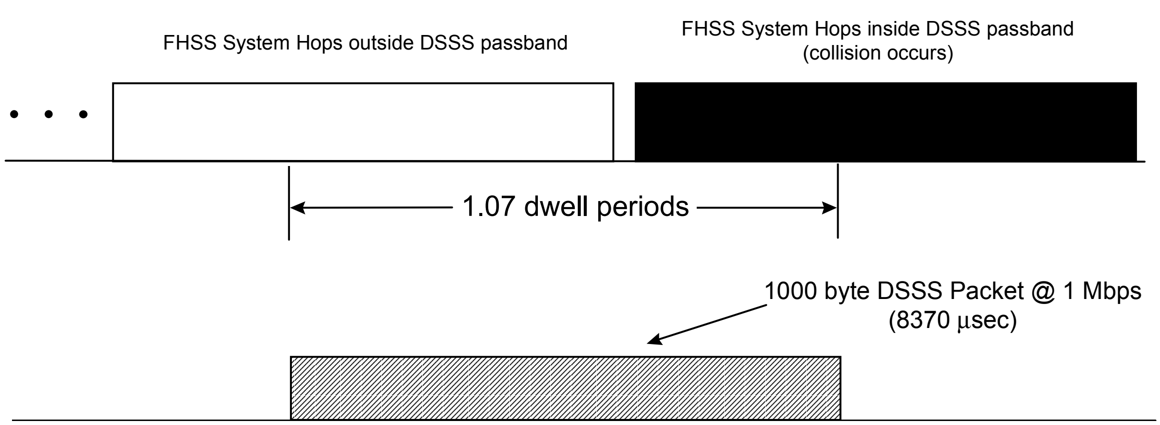


Figure 3.0-1 Probability of Collision Depends on Hop Rate (FHSS System @ 128 hops/sec)

The number of dwell periods overlapped is a function of packet length and the Start-of-Transmission (SOT) time. SOT is a uniform random variable with a range of 0 to t_{dwell}. Based on these considerations and the FHSS system load factor (P_{tx}), the probability of collision for the single DSSS packet under consideration can be computed:

Probability FHSS system hops into DSSS passband (P_{hop}):	25%
Probability of overlapping 2 FHSS dwells ($P_{2\text{-}slot}$):	92.9%
Probability of overlapping 3 FHSS dwells ($P_{3\text{-}slot}$):	7.1%
Probability of FHSS transmission (P_{tx}):	100%

Probability of collision with n slot overlap ($P_{coll}(n)$) $= 1 - (1 - (P_{hop} * P_{tx}))^n$ (1)
$= 1 - (0.75)^n$

Overall Probability of collision (P_{tot}) $= (P_{2\text{-}slot} * P_{coll}(2)) + (P_{3\text{-}slot} * P_{coll}(3))$ (2)

$= ((0.929 * 0.4375) + (0.071 * 0.5781))$

$= 44.7\ \%$

Consider the same situation, with the exception that hop rate is increased to 512 hops/sec:

Case 2:

HR	=	512 hops/sec
P_{hop}	=	25%
P_{tx}	=	100 %
L_{packet}	=	8370 usec

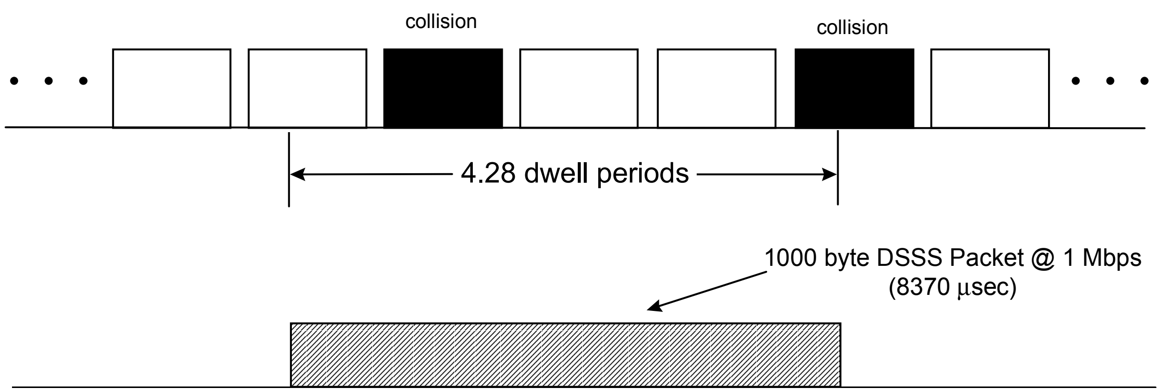


Figure 3.0-2 Increasing Hop Rate Increases Probability of Collision (FHSS System @ 512 hops/sec)

Note that the higher hop rate increases the number of dwell periods overlapped by the DSSS packet. In this situation, the DSSS packet overlaps either five dwell periods or six dwell periods, depending on the start-of-transmission time. The probability of collision for the single DSSS packet under consideration can be computed:

Probability FHSS system hops into DSSS passband (P_{hop}):	25%
Probability of overlapping 5 FHSS dwells ($P_{4\text{-}slot}$):	72%
Probability of overlapping 6 FHSS dwells ($P_{5\text{-}slot}$):	28%
Probability of FHSS transmission (P_{tx}):	100%

Overall Probability of collision (P_{tot}) $= (P_{5\text{-slot}} * P_{coll}(5)) + (P_{6\text{-slot}} * P_{coll}(6))$ (3)

$= ((0.72 * 0.684) + (0.28 * 0.76))$

$= 77.9\ \%$

All parameters in Cases 1 and 2 are held constant, except for hop rate. As hop rate is increased, the collision rate increases as well. Therefore, increasing hop rate does not mitigate interference to DSSS users in the 2.45 GHz ISM band. The Probability of Collision is plotted as a function of hop rate for the stated conditions in Figure 3.0-3. Note that as hope rate is increased, the collision rate increases monotonically. There is no point on the curve at which the Probability of Collision *decreases* as hop rate *increases*. This result also holds true when *both* the victim and the jammer are FHSS systems.

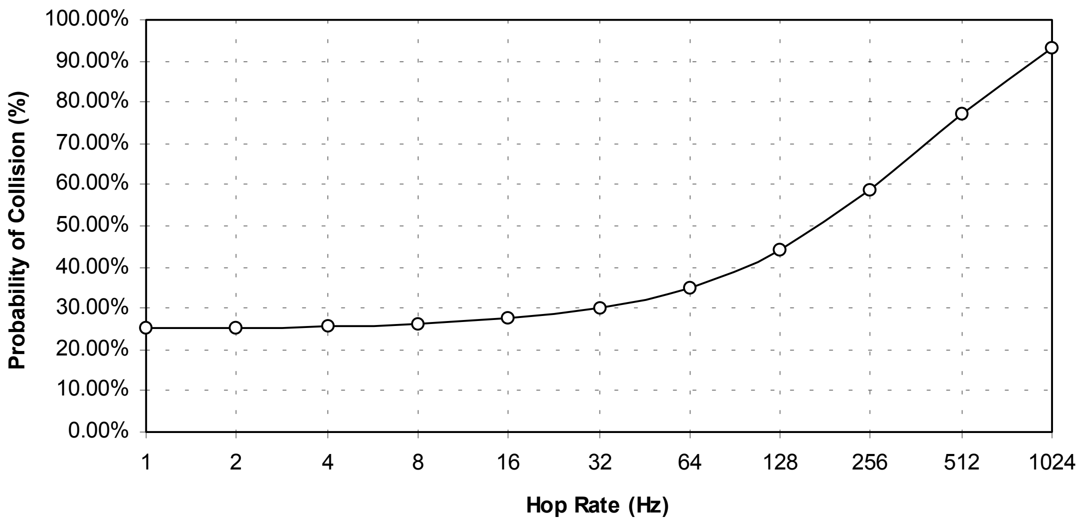


Figure 3.0-3 DSSS Probability of Collision as a Function of FHSS Hop Rate (1000 byte DSSS Packets)

3.1 Impact of Higher Hop Rate on Throughput

In general, in FHSS systems which deal with packet data can deliver higher throughput with a slower hop rate. Increasing hop rate reduces throughput mainly via two mechanisms: more down time due to channel switching, and lost time at the end of a dwell period.

Current FHSS systems require about 200 - 300 usec to switch channels. Therefore, hopping faster results in more time spent switching between channels. Assuming a 250 usec channel switching time, a system hopping at 10 Hz would lose 0.025% throughput due to channel switching (2500 usec / sec). By comparison, the same FHSS system hopping at 1000 Hz would lose 25% throughput due to time lost in channel switching (250,000 usec / sec).

There is another effect which can be of significance for systems which employ Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA) medium access methods. This is one form of a "listen before talk" medium sharing method. IEEE 802.11, HomeRF, and Open Air radios are among those employing this mechanism. Because the timing of traffic is somewhat random, time can be lost at the end of a dwell time if there is insufficient time remaining to transmit a packet of some arbitrary length before switching channels.

In either case, increasing hop rate actually decreases throughput for FHSS networks. Bluetooth radios hop at 1600 hops/sec. However, they can increase throughput by using multiple time slot packets. In this mode, a Bluetooth radio can dwell on one channel for up to 5 time slots. As a result of using longer dwell periods, the hop rate in this mode is lower. In other words, Bluetooth radios actually reduce hop rate in order to increase throughput.

3.2 So Why Do Some FHSS Radios Use Higher Hop Rates?

Channel distortion and interference are the two main mechanisms by which communications in FHSS systems are disrupted. Regardless of which mechanism is at work, increasing the hop rate increases the number of disruptions, but reduces the duration of each disruption by a corresponding amount. This characteristic can be exploited where Quality of Service (QoS) is more important than peak throughput.

Recall from the previous section that increasing the hop rate decreases throughput for an FHSS system. However, for many services such as toll grade voice, throughput requirements are relatively modest (full duplex @ $\leq$ 64 kbps). When supporting telephony, timing of delivery of the digitized voice and reliability of reception are paramount.

Consider the case of a Bluetooth piconet which is supporting a two way voice conversation. Bluetooth features packet structures which support both data and isochronous voice services. In order to deliver robust voice services, Bluetooth uses three different types of voice packets. The most robust packet format uses 1/3 rate Forward Error Correction (FEC) to support Continuous Variable Slope Delta (CVSD) voice encoding. When using this level of FEC, upstream and downstream traffic are sent on alternating time slots as shown in Figure 3.2.1.

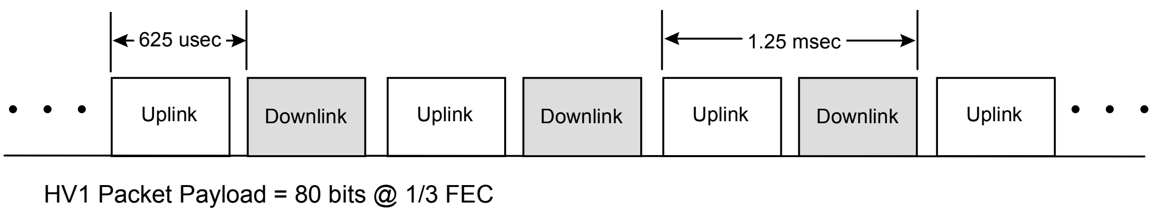


Figure 3.2.1 Bluetooth Piconet TDMA Scheme for Delivery of Voice via 1/3 Rate FEC

When delivering voice services, Bluetooth radios change channels at 1600 hops/sec. If a single voice packet is corrupted in this mode, only 1.25 msec of voice is lost. This is imperceptible to the listener. Assuming that the radio hops to a subsequent channel which is not distorted or jammed, the user will perceive no disruption or degradation of voice quality. If Bluetooth hopped at a slower rate, the amount of voice lost due to a corrupted packet would be correspondingly longer. At some point, a single lost voice packet could become perceptible to the listener. This example is illustrative because Bluetooth trades throughput in this mode to provide extremely robust voice transmission capable of maintaining very high QoS.

4.0 Conclusions

The power reductions proposed by HomeRF are inadequate to ensure that other users of the band will not encounter increased levels of interference. Expansion in the occupied channel width reduces the number of orthogonal (non-overlapping) channels in the band. In a ruling regarding operation of FHSS radios in the 915 MHz band, the Commission concluded that linear power reduction in proportion to the reduction in the number of channels was inadequate to protect other users. In addition, the proposed limits for WBFH radios would allow transmission at power levels which are higher than those used by the vast majority of radios currently operating in the band.

The analysis presented in this paper demonstrates that increasing hop rate does not reduce interference to other Part 15 users. In fact, increasing hop rate actually increases the rate of collision with other users. It is reasonable to conclude that authorized users will suffer a similar impact. It has further been shown that increasing hop rate reduces throughput for FHSS systems. Due to the higher hop rate, periods of interference with other users such as DSSS radios or conventional FHSS radios are more frequent, but of a shorter duration. In applications where QoS is of greater importance than peak throughput, this property can be exploited to provide services such as telephony.

Under current regulations, manufacturers of FHSS equipment have the latitude to select a hop rate suited to their particular application. If maximum throughput is desired, the hop rate can be set as low as 2.5 Hz. If TDMA support of isochronous services is sought, a higher hop rate can be selected. Therefore, there should be no regulatory prohibition against use of faster hopping, nor should the FCC *require* faster hop rates due to the fact that this will increase interference to other users of the spectrum.

The proposal put forward by HomeRF is similar to an earlier proposal to widen FHSS channel widths which was rejected by the Commission (ET Docket 96-8). The only salient differences are that the HomeRF scheme calls for the use of overlapping channels and a higher hop rate. Both measures have been shown to increase interference to other users in the band. In addition, due to susceptibility to multipath, WBFH systems will not be able to provide sufficient throughput to deliver the benefits to consumers claimed by its proponents. The HomeRF proposal should therefore be rejected.

References

1. HomeRF Working Group Technical Committee, *"Technical Material in Support of the Wider Channel Bandwidth Proposal for 2.4 GHz Frequency Hopping Regulations",* presented to OET, Feb. 25, 1999
2. Padgett, J., *"The Effect of System Parameters on the Interference Potential of Frequency Hopping Systems in the ISM Bands*", Submission to OET (ET Docket 96-8), June 14, 1996.
3. Zyren and Gandolfo*, "Analysis and Simulation of Overlapped Frequency Hopping Channels"*, Submission to OET (ET Docket 99-231), Sept. 1999.
4. Ennis, "*Impact of Bluetooth on 802.11 Direct Sequence Wireless LANs*", Doc.: IEEE802.11-98/319a, Sept. 1998.