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Effects of Microwave Interference On IEEE 802.11 WLAN Reliability

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Abstract

The influence of microwave oven interference on IEEE802.11 Wireless Local Area Network (WLAN) performance is a significant factor because they share common spectrum in the 2.400 - 2.4835 GHz Industry, Science, and Medicine (ISM) band. FCC regulations permit radiated power of up to 1 watt in this band provided spread spectrum techniques are employed. Spread spectrum methods facilitate multiple users sharing the same spectrum in an unlicensed environment and offer interference rejection properties. There are two spread spectrum techniques addressed by FCC regulations (15.247). These are Direct Sequence Spread Spectrum (DSSS) and Frequency Hopped Spread Spectrum (FHSS). Because of the significant differences in the two methods, the effects of microwave oven (MWO) interference are quite different on systems employing these techniques.

This paper describes MWO interference and presents a model which is useful in predicting WLAN reliability. The mechanisms by which the interference disrupts system performance for DSSS and FHSS are described separately. Finally, quantitative results showing packet error rate (PER) under varying levels of interference and packet length are presented and discussed.

Summary

This paper describes the results of an analysis of the effects of varying packet length and interference level on the reliability of WLANs in the presence of microwave oven (MWO) interference. There are four different aspects of this analysis.

Section I deals with modeling interference from microwave ovens. The results of an NTIA report on interference from MWO in the 2.4 GHz ISM band are summarized along with some relevant journal articles. A model of MWO interference presented by Motorola before the IEEE 802.11 WLAN Working Group is discussed. A MWO can be effectively modeled as a swept narrowband jammer with a 50% duty cycle. The resulting interference is synchronized to the 60 Hz AC power line voltage due to the fact that the magnetron power supplies are only half wave rectified.

Section II includes a basic review of the performance of FHSS systems in the presence of narrow band jammers. FHSS systems combat MWO interference by avoiding it. Performance curves are presented which show Packet Error Rate (PER) as a function of both packet length and interference level. Based on the model presented, it is shown that the best line of defense for an FHSS system is a short packet length. This will permit the successful transmission of smaller packets between bursts of interference.

Section III extends this discussion to DSSS systems. DSSS systems have wide occupied bandwidths. This increases the probability that MWO interference will fall "in band". However, the effect of processing gain and the underlying modulation method must be considered. The DBPSK/DQPSK modulation method employed in DSSS radios is considerably more robust than the 2FSK/4FSK method employed by IEEE 802.11 FHSS systems. In addition, the despreading process spreads the bulk jammer power out of band, giving an additional 10 dB improvement in radio performance over non-spread methods. The remaining in-band noise is incoherent white noise. DSSS systems deal with MWO interference by suppressing it, not by avoiding it.

Section IV summarizes the data and provides an interpretation. The results demonstrate that FHSS receivers can transmit short packets (100 - 200 bytes) even in even a very noisy environment. However, when using longer packets (1000 bytes), FHSS systems require a signal strength of 16 to 17 dB above peak interference levels to achieve reliable operation in the presence of MWO interference when operating at 1 Mbps. This effect is even more pronounced when operating at 2 Mbps.

By contrast, packet error rates can be high even for short packets when interference levels exceed signal strength in DSSS systems. Once signal power is roughly equal to jammer power, the DSSS systems can provide reliable operation, regardless of packet length. A DSSS system can reliably receive 1000 byte packets with a signal-to-jammer power ratio of roughly 0 dB, based on the analysis presented. Experience has shown that DSSS systems can operate reliably even in very close proximity to a microwave oven. Analysis such as this provide a good framework for discussion of the MWO interference question, but the most convincing method is a side-by-side test of FHSS and DSSS systems in the presence of an operating microwave oven.

Section I: Model of Microwave Oven Interference

The results of extensive measurements of interference form fourteen different microwave ovens were summarized in a two volume NTIA report [1,2]. The report demonstrates that the interference has roughly a 50% duty cycle with a 16.7 msec period. This is due to the fact that the magnetrons in the ovens are driven by 60 Hz AC power and are active during only half of the sinusoidal line voltage cycle.

Frequency domain measurement of one of the tested MWO is shown in Figure I-1. The measurements were taken using a spectrum analyzer in the "max hold" mode. Peak levels and interference bandwidth vary considerably among ovens from different manufacturers.
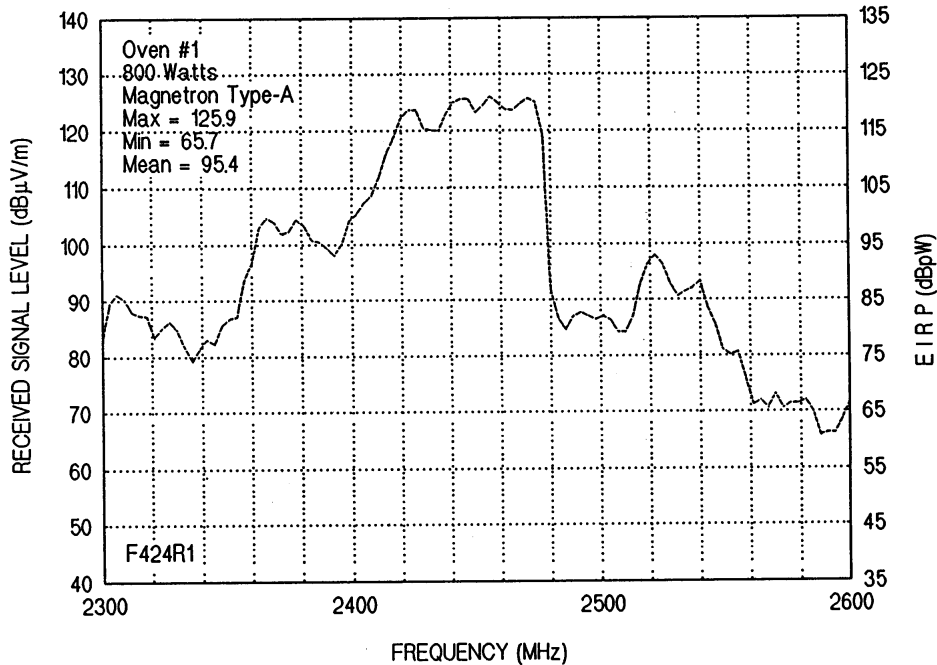
Figure I-1   "Max-Hold" Amplitude vs. Frequency Plot of MWO Interference from NTIA report

The results of the NTIA tests are informative, but the "max hold" frequency domain measurements give an overly pessimistic view of the MWO interference problem. Subsequent measurements [3] using spectrographic techniques show that the instantaneous interference is actually very narrow band. Further, the frequency is swept over a significant portion of the ISM band as the power line voltage across the magnetron varies on each positive half cycle of the 60 Hz sinusoid.

A representation of a spectrographic plot is shown in Figure I-2. Of critical importance are the swept frequency range (f_{swept}) and channel dwell time (t_{dwell}). It has been pointed out that any time an FHSS radio dwells on a channel within the range of swept frequencies for more than 16.7 msec, it will be hit at least twice by interference [4]. As previously mentioned, f_{sweep} varies considerably among ovens from different manufacturers.
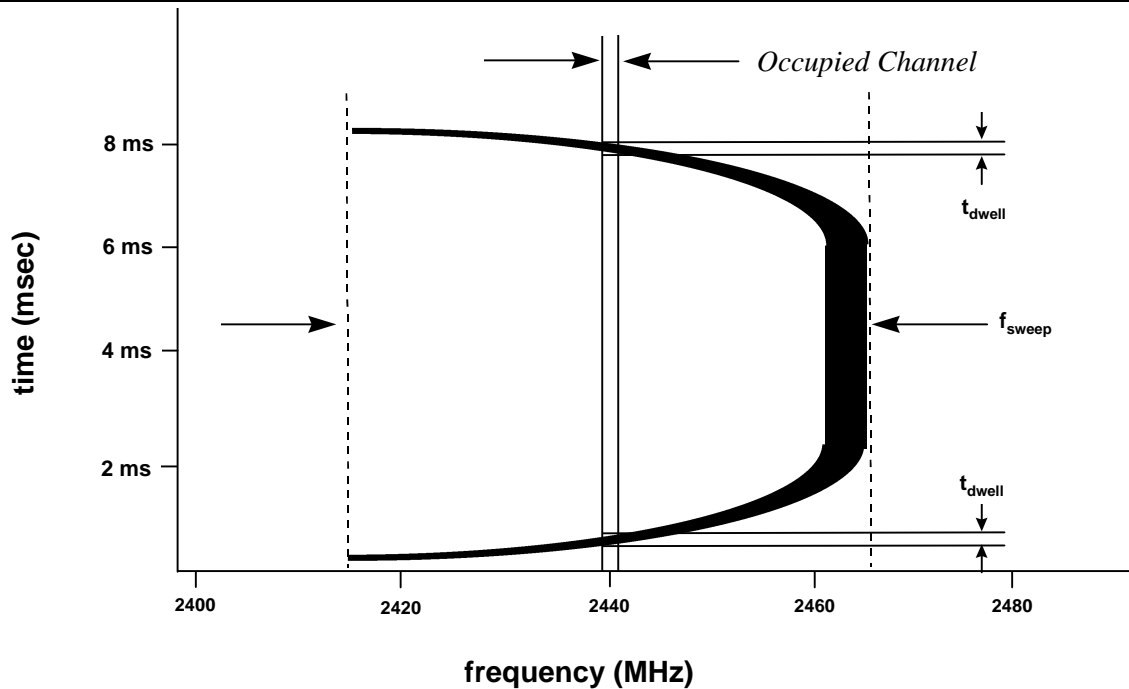
Figure I-2   Spectrographic Plot of Microwave Oven Interfernce

In order to estimate the effects of packet length on system throughput for IEEE802.11 WLAN's, the foregoing characteristics of MWO interference have been incorporated into a simple but useful model [4]. The range and rate of frequency sweep determine channel dwell time, t_{dwell}. Even when operating in the presence of FHSS systems having a relatively narrow occupied bandwidth, t_{dwell} is long enough to ensure that multiple bits will be jammed as the MWO interference sweeps through a given channel. Worst case assumptions would be a swept frequency range of the entire 83 MHz of the 2.4 GHz ISM band over 0.8 msec (10% of the 8 msec "on" time for the magnetron). Assuming a channel width of 1 MHz and 80 separate non-overlapping channels, the number of corrupted bits would be:

$$t_{dwell} \quad = \; 0.8 \text{ msec} / 80 \;\; \text{channels}$$
$$= \; 10 \text{ usec}$$

$$\text{\# exposed bits} \;\; = \; 1 \text{ Mbps} * 10 \text{ usec}$$
$$= \; 10 \text{ bits}$$

Typical channels dwell times are much longer for DSSS systems because the occupied channle width is significantly larger (20 MHz for DSSS compared to 1 MHz for FHSS).   This simple analysis demonstrates that the channel dwell time is sufficient even under worst case conditions to for several bits to be exposed to interference. Typical swept frequency range for domestic microwave ovens is about 50 MHz.
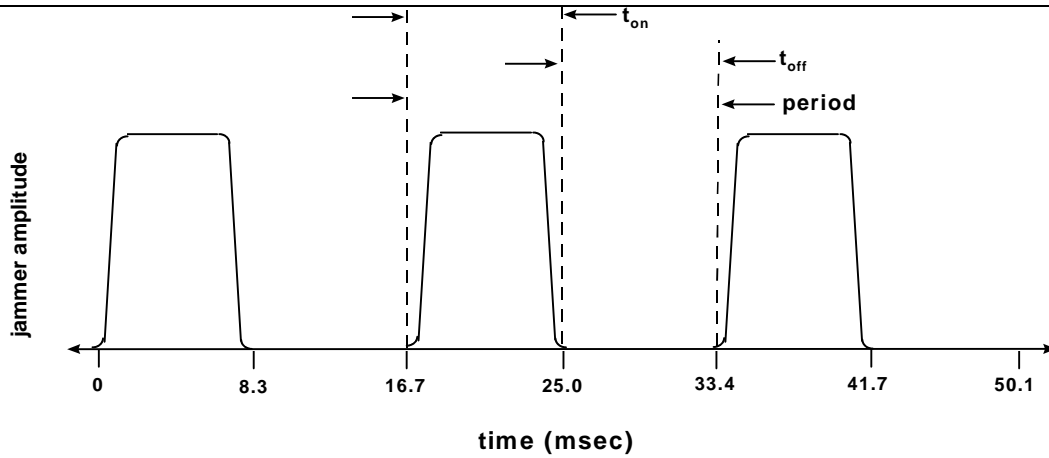
Figure I-3   Microwave Oven Magnetron Duty Cycle

In summary, MWO interference can be characterized as a swept narrowband jammer having a swept frequency range, f_{sweep}, and a channel dwell time, t_{dwell} . The jammer is active over 50% of 60 Hz power line cycle and, therefore, has a period of 16.7 msec. Further, due to the fact that the jammer frequency sweeps on both the *on/off* and *off/on* transients, an individual channel lying within the range of swept frequency will experience two periods of jamming on each cycle of the 60 Hz power line voltage as shown in Figure I-4.
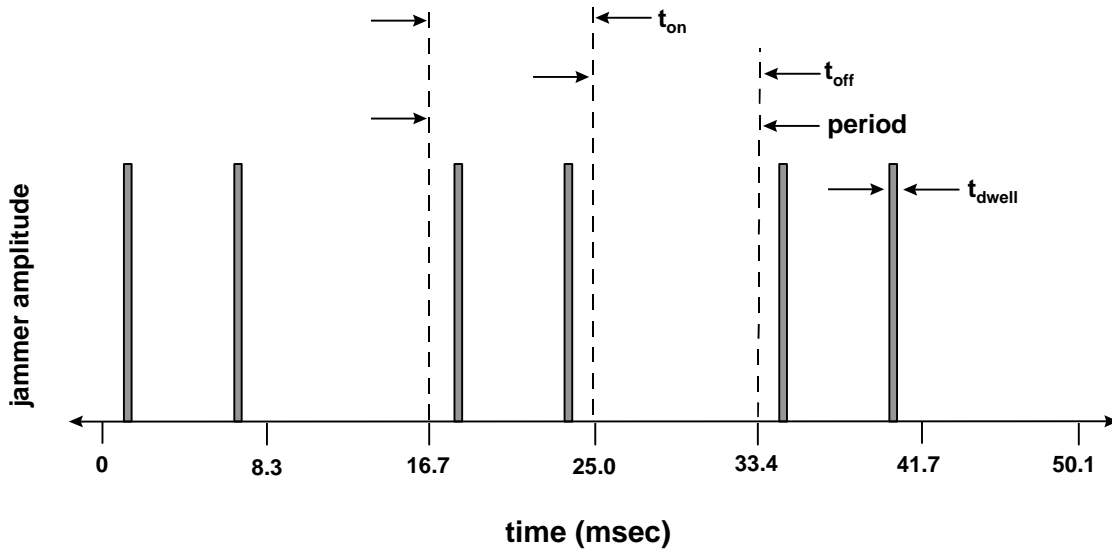
Figure I-4   Microwave Oven Interference in Single FHSS 1 MHz Channel

This model provides a good starting point from which to analyze the effects of MWO interference. In practice, the picture is obscured by the fact that the magnetron initially pulses as the voltage starts to ramp up on the half sine wave. It also pulses as the magnetron shuts down on the falling edge of the power line voltage sine wave. In addition, swept frequency and radiated emission levels vary as a function of oven load. Nevertheless, this basic model provides a means of analyzing the effects of hop rate and packet length.

Section II: FHSS Systems and Microwave Oven Interference

FHSS systems which operate in accordance with FCC Part 15 rules (15.247) must divide the 83.5 MHz of the ISM band into at least 75 separate channels, with each channel having a maximum width of 1 MHz. The utilization for each channel cannot exceed 400 msec in any 30 second period. Therefore, each channel must get equal utilization when averaged over a 30 second period.

FHSS Modulation Method

IEEE802.11 FHSS systems operate at 2 Mbps using 4-level Frequency Shift Keyed (4FSK) modulation, and 1 Mbps using 2-level FSK (2FSK) modulation. In order to fit 1 or 2 Mbps into a 1 MHz channel, an extremely low modulation index (h) is used. Modulation index is defined as:

$$h = \Delta F / R$$

where   h   = modulation index
                ΔF = frequency deviation between mark and space
                R   = data rate (bps)

The modulation index is 0.32 for 2FSK and 0.16 for 4FSK. Bit error rates for IEEE802.11 2FSK and 4FSK are shown in Figure II-1. In order to provide 1 and 2 Mbps speed through a 1 MHz occupied bandwidth, extremely narrow frequency deviations were used. The result is a very high signal strength (Eb/No) is required to achieve reliable operation, as measured by Bit Error Rate (BER).
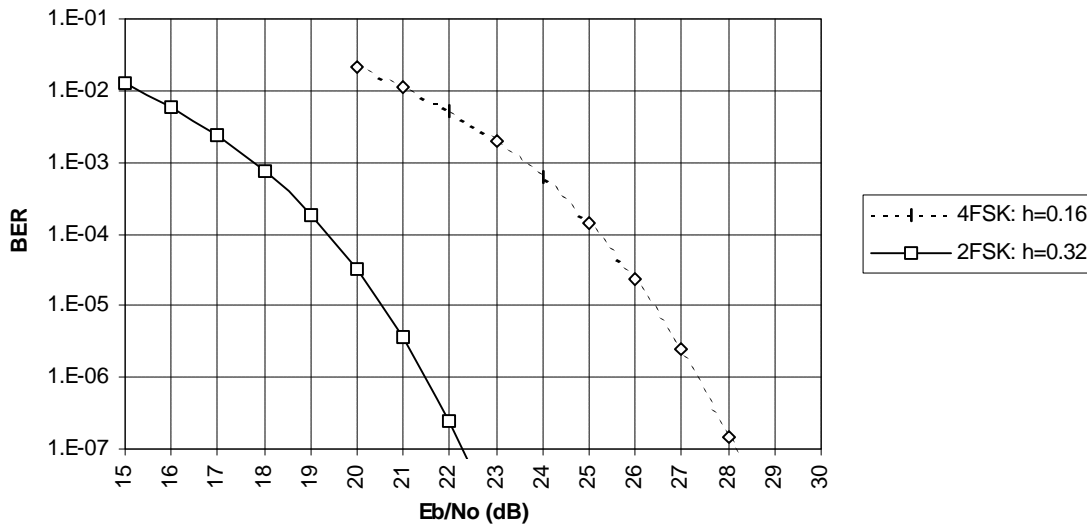
Figure II-1 Bit Error Rate as a Function of Eb/No for 2 and 4 Level FSK

If the bit errors within a packet were uncorrelated random events, extending the results for bit error rate (BER) to packet error rate (PER) would be a straightforward matter. However, it has now been shown that the interference from microwave ovens is not purely random in nature. In addition, the systems under consideration are decidedly slow hoppers. Therefore all bits within a packet are transmitted on the same frequency. Bit errors within a packet are therefore not uncorrelated events.

In order to perform an analysis of throughput, some assumptions about swept frequency range and sweep rate must be made. Data gathered from lab tests at Harris Semiconductor, as well as published test data [1,2] indicate that the range of swept frequency for domestically produced microwave ovens is about 50 MHz. A sweep rate of 0.8 msec for the on/off and off/on transients is also assumed. This is consistent with the model described above [4], as well as published spectrographic data [3].

For the purpose of this analysis, it is assumed that the MWO interference can be treated as white noise within the relatively narrow occupied channel (1 MHz) of an FHSS radio. Magnetrons are inherently narrowband devices due to the geometry of the tuned cavities. However, under loading the resonant bandwidth, or Q, expands significantly and has an instantaneous bandwidth on the order of 500 kHz. In addition, the MWO interference is swept during off/on and on/off transients (described in Section I) and the exact instantaneous location within the occupied channel is purely random. The low modulation indicies for 2FSK and 4FSK, 0.32 and 0.16, result in extremely high symbol cross-correlation coefficients (ρ), 0.85 and 0.95 respectively. For noncoherent receivers, the symbol cross-correlation is computed by:

$$\rho \;=\; \frac{\sin\pi h}{\pi h}$$

where p = sysmbol cross correlation coefficient
      h = modulation index

High symbol cross correlation will cause any in-band interference to have approximately the same effect on both the mark and space decision variables, regardless of its precise location within the occupied channel.

It is further assumed that a single bit error will cause the CRC to indicate a bad packet, resulting in a packet error. Based on the assumption that a single bit error results in a packet error, the effects of the scrambler can be neglected. The only means of avoiding packet errors is to avoid periods of interference, or to overcome it with sufficient signal strength.

MWO Interaction with FHSS Signals: Analysis by Conditional Probabilities

PER can be estimated by the use of conditional probabilities. As shown in Figure II-2, the occupied channel of a FHSS radio will fall into one of three regions relative to the MWO interference. If the occupied channel falls outside the range of swept frequency (f_{sweep}), no interference will occur (Condition A). If the occupied channel falls within the range of swept frequency, the receiver will either experience intermittent periods of interference during magnetron transients (Condition B), or prolonged periods of interference (Condition C). For Conditions B and C, the probability of successful transmission is a function of packet length [4]. This model is described briefly below and in greater detail in the Appendix.
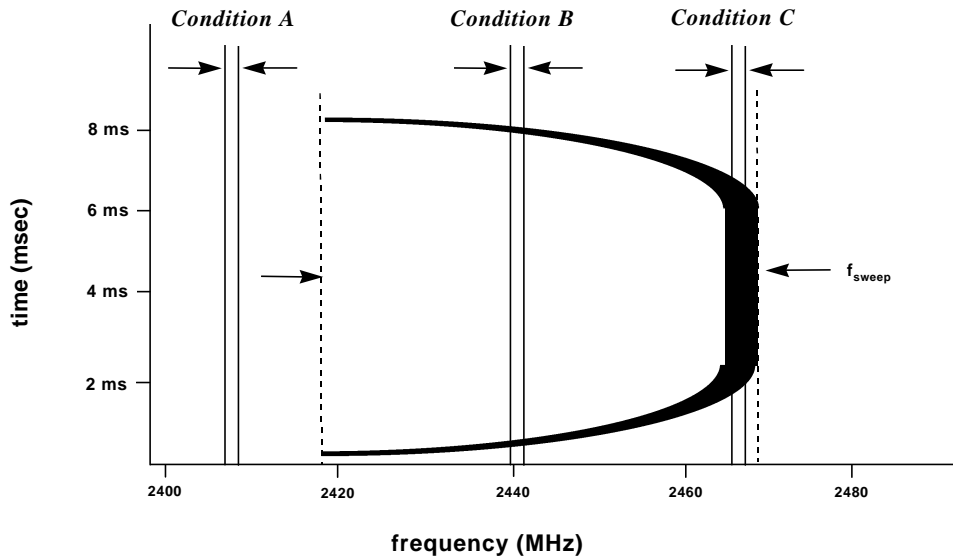
Figure II-2 Possible Conditions for Occupied Channel in Presence of MWO Interference

There are three possible conditions for the occupied channel in the presence of MWO interference:

Condition A: Occupied Channel lies outside the range of swept frequency. In this case, data transmission is assumed to be error free.

Condition B: Occupied Channel lies within the range of swept frequency, but is jammed only during on/off and off/on transients of the magnetron.

Condition C: Occupied Channel lies within the range of swept frequency, and the occupied channel lies on same frequency as magnetron steady state operation.

These conditions are exhaustive and mutually exclusive. Therefore:

$$P_A + P_B + P_C = 1$$

Condition A

In this situation, the FHSS channel lies outside the range of occupied frequency. The likelihood of this condition (P_A) is:

$$P_A = (83.5 \text{ MHz} - f_{sweep}) / 83.5 \text{ MHz}$$

For this condition, data transmission is assumed to be error free. The implication is that there is some minimum level of system reliability, regardless of the level of interference.

Condition B

For Condition B, the occupied channel lies within the range of swept frequency, but experiences only brief periods of interference during off/on and on/off transients of the magnetron. It is further assumed that the interference from the magnetron is <1 MHz once it reaches a steady state condition. The probability of Condition B (P_B) is therefore:

$$P_B = (f_{sweep} - 1 \text{ MHz}) / 83.5 \text{ MHz}$$

A time domain representation of microwave interference for Condition B is shown in Figure II-3. From this figure, it becomes apparent that packet length is the dominant factor which determines PER under this condition. Packets longer than 9.2 msec have no chance of avoiding interference.
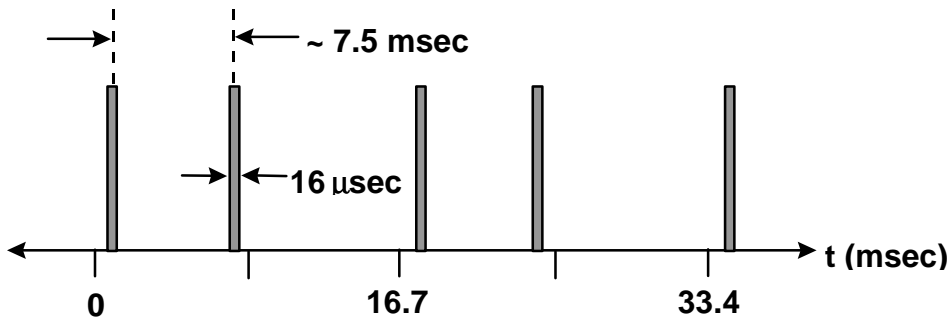
Figure II-3 Time Domain Representation of MWO Interference for Condition B

Condition C

In this case, the occupied channel for the radio coincides with the steady state operating frequency of the MWO magnetron. This is the worst case condition, due to the relatively large duty cycle of interference in this channel, as shown in Figure II-4. Fortunately, the severity of this condition is mitigated by the relatively low probability of its occurrence. The MWO is modeled as a narrowband jammer once it reaches steady state after the off/on transient. It has a bandwidth < 1 MHz, and therefore can only jam a single channel. The probability of Condition C (P_C) is:
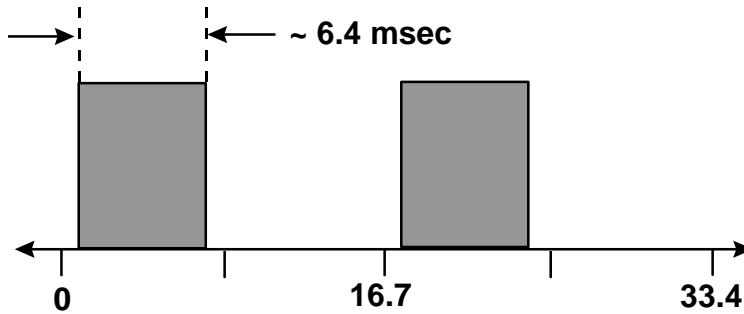
$$P_C = 1 \text{ MHz} / 83.5 \text{ MHz}$$

Figure II-4 Time Domain Representation of MWO Interference for Condition C

FHSS Receiver Sensitivity

Inclusion of the effect of receiver sensitivity requires an additional conditioned probability. The model must include an estimate of the number of bits (n) exposed to interference (but not necessarily erroneous) when transmitted during burst of jammer energy. PER For Condition B is then estimated as follows:

$$PER_B = P_B * P_{MWOB} * [1 - (1 - P_e)^n]$$

where:

PER_B = Packet Error Rate given Condition B
P_B = Probability of Condition B
P_{MWOB} = Probability of encountering MWO interference given
   Condition B
P_e = Probability of bit error
n = estimate of number of corrupted bits

Conditions A, B, and C are mutually exclusive and exhaustive. Total PER is therefore the sum of the PER under each of the three conditions (PER under Condition A is assumed to be zero). For a more detailed description method employed to include receiver sensitivity, see the Appendix. PER has been computed as a function of relative jammer power (Eb/Jo) for several values of packet length at 1 Mbps and 2 Mbps, as shown in Figures II-5 and II-6 respectively.
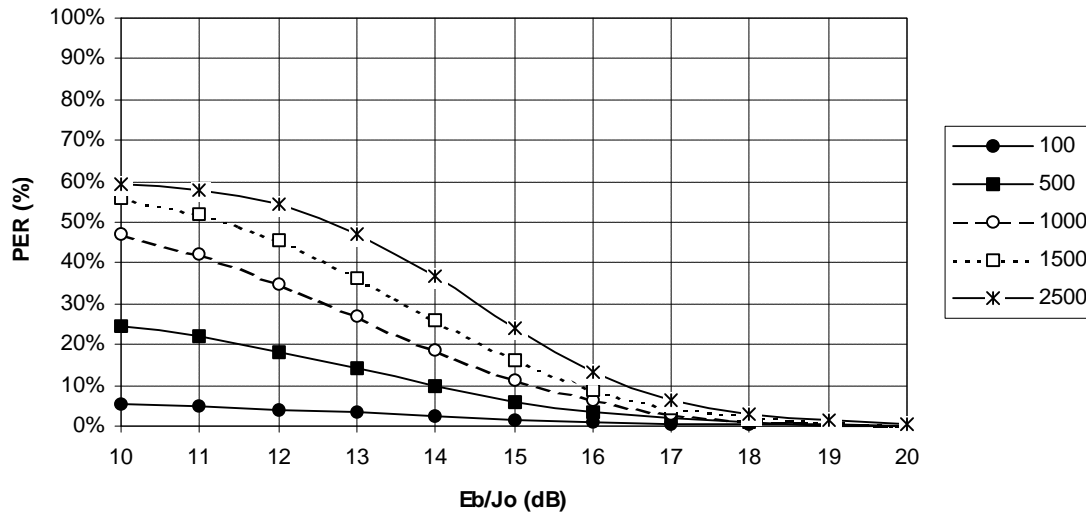
Figure II-5 FHSS PER as a Function of Packet Length (bytes) and Relative Jammer Power @ 1 Mbps
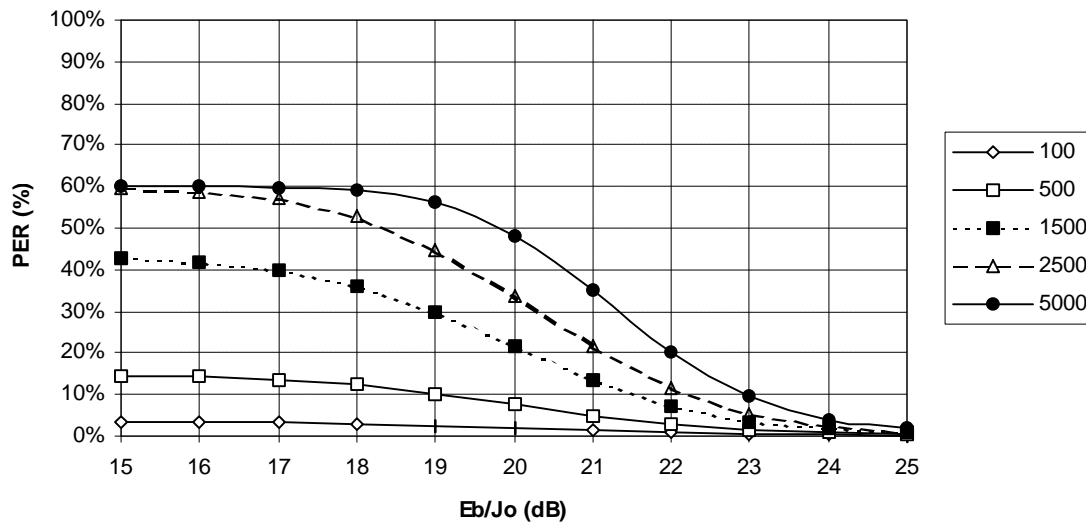
Figure II-6 FHSS PER as a Function of Packet Length (bytes) and Relative Jammer Power @ 2 Mbps

These results demonstrate that the signal strength for an FHSS radio must exceed the interference from a MWO by about 16 dB when operating in the 1 Mbps mode before reliable packet reception (PER < 10%) is possible for longer packets. However, shorter packets (100 to 200 bytes) can be received reliably even in a high interference environment because of their ability to avoid bursts of jammer energy. The difference between error rates for long and short packets is even more pronounced at 2 Mbps. Short packets are still able to avoid MWO jammer bursts, however longer packets require as much as 22 dB Eb/Jo for reliable transmission.

Section III: *DSSS Systems and Microwave Oven Interference*

Operating rules for DSSS systems in the ISM band are covered under the same section of the FCC regulations as the FHSS systems (15.247). By these regulations, DSSS systems do not have an occupied bandwidth restriction but must have a minimum of 10 dB processing gain. IEEE 802.11 DSSS

systems have an occupied bandwidth of roughly 20 MHz. Processing gain is realized by modulating each data bit with an 11 bit Barker code (pseudo random sequence). Processing gain is therefore 11:1, or 10.4 dB.

DSSS Modulation Method

      IEEE802.11 DSSS systems employ Differential Binary Phase Shift Keying (DBPSK) and Differential Quadrature Phase Shift Keying (DQPSK) for 1 Mbps and 2 Mbps modulation, repectively. BER curves for these modulation methods are shown in Figure III-1. Note that the required Eb/No for a BER of 10^{-5} is 10 dB for DBPSK and 12 dB for DQPSK.
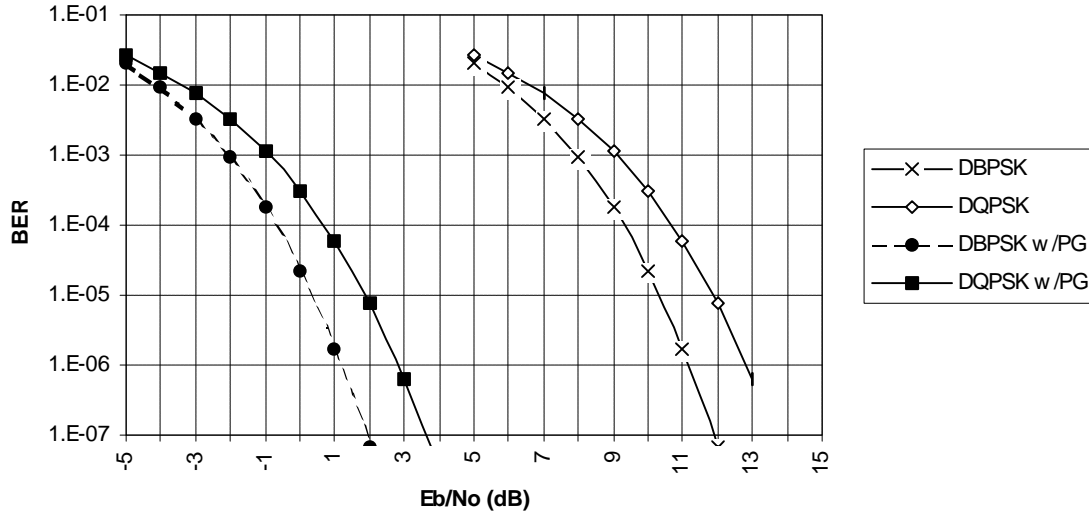
Figure III-1 Bit Error Rate as a Function of Eb/No for DBPSK/DQPSK and DBPSK/DQPSK with Processing Gain

      Aside from a more power efficient modulation method, DSSS systems also provide processing gain against narrow band jammers, including microwave ovens. As described above, the level of processing gain is 10 dB. There are two main effects of the "despreading process":

      a. Narrowband interference is reduced by a factor of 10 dB
      b. Remaining interference is converted to wideband white noise

 The first effect, reduction of interference power, is depicted in Figure III-2 by the curves at the extreme left of the plot. These are simply the BER curves for DBPSK abd DQPSK shifted to the left by 10 dB to indicate the performance improvement in the presence of a narrow band jammer. The second effect, conversion of narrowband interference into white noise, is significant because it facilitates analysis of system performance. A discussion of the mechanics of DSSS processing gain is presented by Dixon [6].

Microwave Oven Interference Effects on DSSS Signals

      The interaction of MWO interference with DSSS signals is quite different than with FHSS signals. Unlike FHSS radios, DSSS radios are not frequency agile. They also have a much greater occupied bandwidth (20 MHz as compared to only 1 MHz for the FHSS radios). While a DSSS radio might be tuned to avoid all or most of the interference in a given scenario, it is equally likely that it could be tuned so that most of the interference falls in-band.

The latter situation is the "worst case" and is the subject of this analysis. It is assumed that the stable operating frequency of the MWO is in the high end of the occupied channel for the radio as shown in Figure III-2. Under this condition, all of the energy for emitted from the MWO once the magnetron frequency stabilizes and most of the emission during the transient condition will fall in band. This is a "worst case" condition for the DS system.
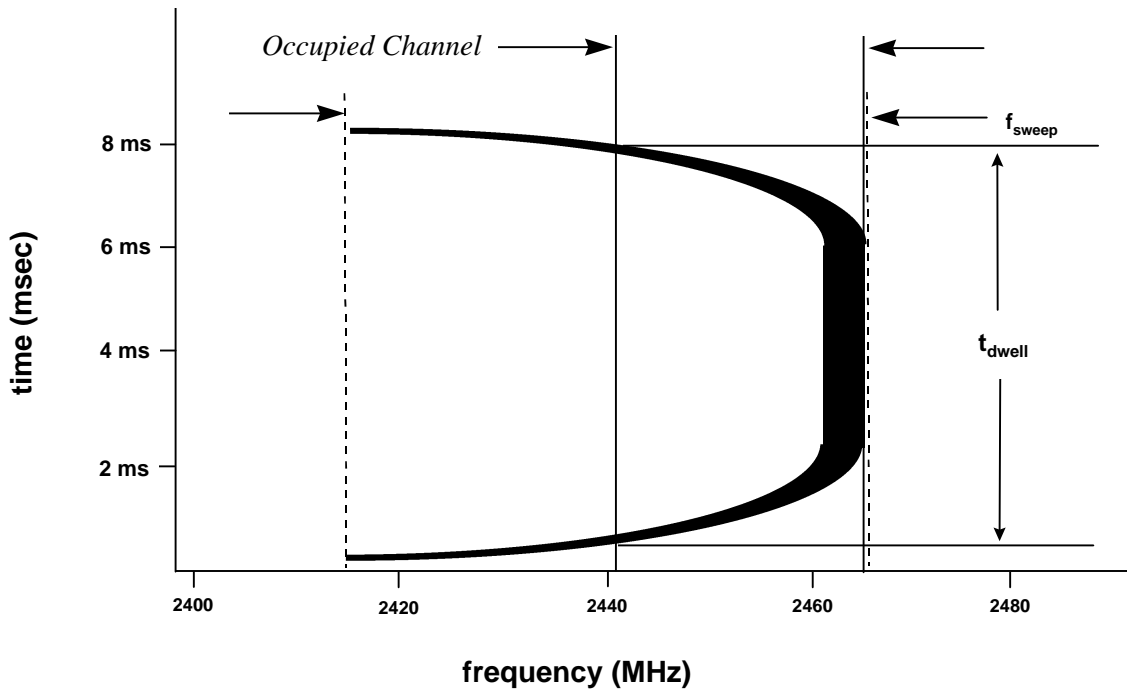

Figure III-2 DSSS Occupied Channel in Presence of MWO Interference

The result of a scenario such as this is that the MWO interference is present in the occupied channel for a period of time which roughly coincides with the magnetron duty cycle. This is analogous to Condition C for the FHSS system described in Section II above, with the exception that the probability of its occurrence is 100% under the stated conditions.
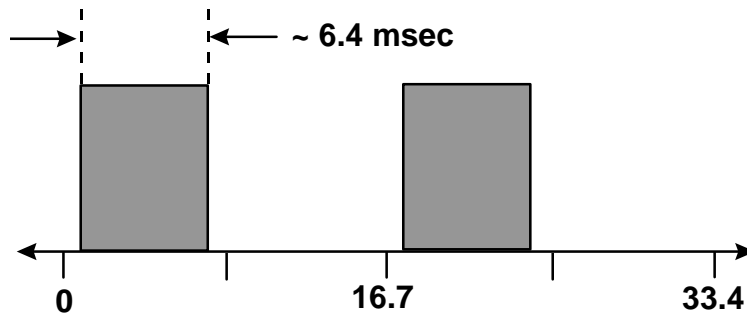

Figure III-3 Time Domain Representation of "Worst Case" MWO Interference in a DSSS System

DSSS Receiver Sensitivity

The DSSS case is a bit more straight forward than the FHSS case, because there are no conditioned probabilities. If the DSSS receiver is tuned as shown in Figure III-2, the effect of MWO interference is computed in exactly that same manner as Condition C for the FHSS case, with the

exception that the BER curves shown in Figure III-1 are used, and the probability of the occurrence of this condition is 100%. Again, the model must include an estimate of the number of bits (n) exposed to interference (but not necessarily erroneous) when transmitted during burst of jammer energy. PER is then estimated as follows:

$$PER = P_{MWO} * [1 - (1 - P_e)^n]$$

where:

PER = Packet Error Rate
P_{MWO} = Probability of encountering MWO
P_e = Probability of bit error (assuming 10 dB Processing Gain)
n = estimate of number of corrupted bits

PER has been computed as a function of relative jammer power (Eb/Jo) for several values of packet length at 1 Mbps and 2 Mbps, as shown in Figures III-4 and III-5 respectively.
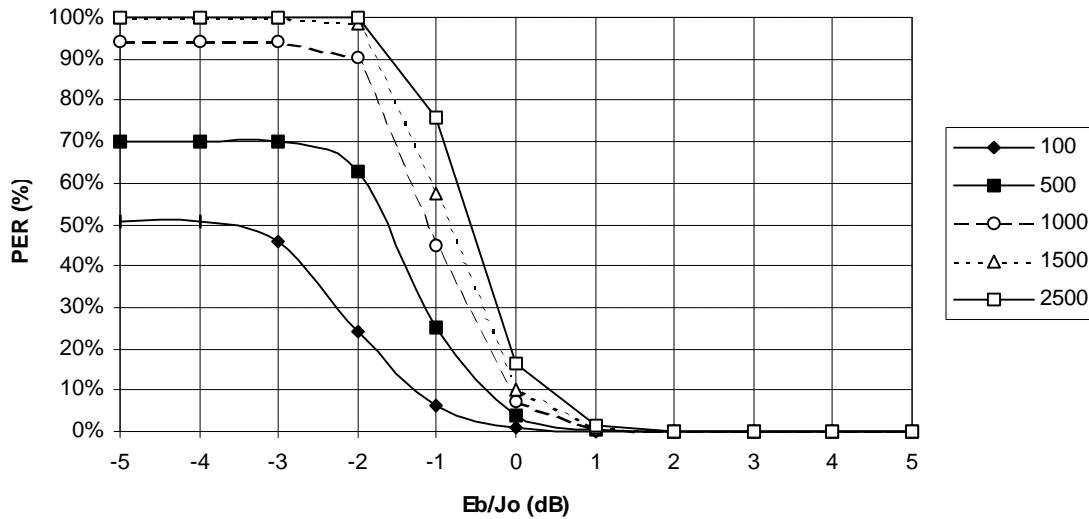
Figure III-4 DSSS PER as a Function of Packet Length (bytes) and Relative Jammer Power @ 1 Mbps
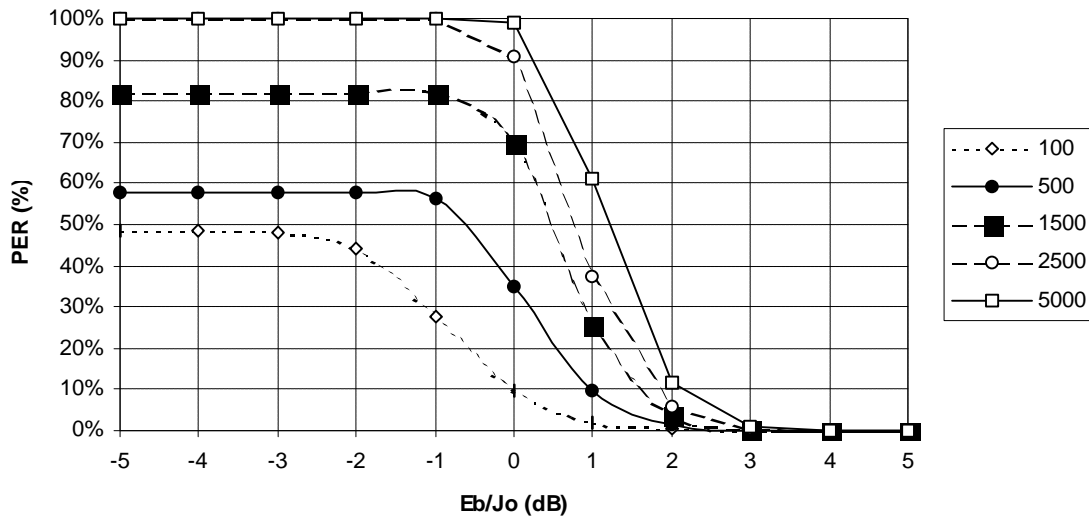
Figure III-5 DSSS PER as a Function of Packet Length (bytes) and Relative Jammer Power @ 2 Mbps

Reliability of the DSSS system is far less dependent on packet length. For extremely high levels of interference, even short packets have a high error rate (50%). However, PER for 100 byte packets drops below 10% with Eb/Jo at about -1dB. For longer packets (2500 bytes), PER drops below 10% with Eb/Jo at 0.5 dB. The reason behind this effect is the DS system does not *avoid* the jammer, it *suppresses* it. Experience has shown that DSSS receivers can operate in very close proximity to microwave ovens and still maintain reasonable throughput.

Section IV: Comparison of Results

The results for both the DSSS and FHSS systems in the presence of MWO interference is summarized in Table IV-1.

Packet Length (bytes)	1 Mbps (Eb/Jo @10% PER)			2 Mbps (Eb/Jo @10% PER)	
	DSSS	FHSS		DSSS	FHSS
100	-1.0	*<10% PER*		0	*<10% PER*
500	-0.5	14		1	19
1000	0.0	15		1.25	21
1500	0.0	16		1.5	21.5
2500	0.5	16.5		2	22
5000	0.75	17		2	23

Table IV - 1   Required Eb/Jo to Achieve 10% Packet Error Rate

By virtue of the narrow occupied bandwidth, FHSS systems are able to avoid interference with short packet lengths regardless of the interference level. Note that the PER remains below 10% for all levels of interference power with short packets (100 bytes) for both the 1 Mbps and 2 Mbps FHSS cases. However, in order to achieve reliable operation with longer packets, a lot of signal energy is required at the receiver.

As packet length increases, the FHSS system can no longer avoid interference. Instead, it must now overpower it. The low modulation indices for both 2FSK at 1 Mbps and, in particular, 4FSK at 2 Mbps drive the signal strength requirement in this situation. For a packet length of 1000 bytes, the FHSS system requires 15 dB Eb/Jo to achieve a 10% PER at 1 Mpbs, and 21 dB Eb/Jo to reach 10% PER at 2 Mbps.

The DSSS system has a much higher occupied bandwidth and is not frequency agile. It can therefore be tuned to a frequency where nearly all of the MWO interference falls within the occupied channel. Interference avoidance is not possible for DSSS systems in such a situation. This is offset by two features of IEEE802.11 systems:

a. The DBPSK/DQPSK modulation method is more power efficient than the 2FSK/4FSK modulation employed by FHSS systems

b. IEEE802.11 DSSS systems reject about 90% of the energy of a narrow band jammer such as a microwave oven

Table IV-1 shows that PER for DSSS systems can be very high even for short packets when jammer power exceeds signal strength. However, once signal power is at or above jammer power, the DSSS system provides reliable operation regardless of packet length. In terms of the real world environment, experience has shown the DSSS systems can operate reliably in very close proximity of a microwave oven.

This analysis studies the effects of MWO interference in isolation. There are other effects such as signal attenuation and multipath that are of at least equal importance in terms of determining overall WLAN reliability. This paper represents an attempt to provide a framework for discussing the MWO interference issue in a quantitative manner. As always, the best means determining which system is better in a given application is via side-by-side system testing.

References

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Appendix A: Model of MWO Interference on FHSS Radios

This analysis is based on a few simple conditional probabilities. It is assumed that data transmission is error free in the absence of MWO interference. It further assumes that one bit error will cause a packet error. In that case, the CRC check will fail and the packet is invalidated. Given the assumption that one bit error will cause a packet error, the effects of scrambling can be neglected. The occurrence of multiple errors at the output of the data descrambler (one error for each term in the polynomial) in the event of one bit error at the input does not change the probability of a packet error.
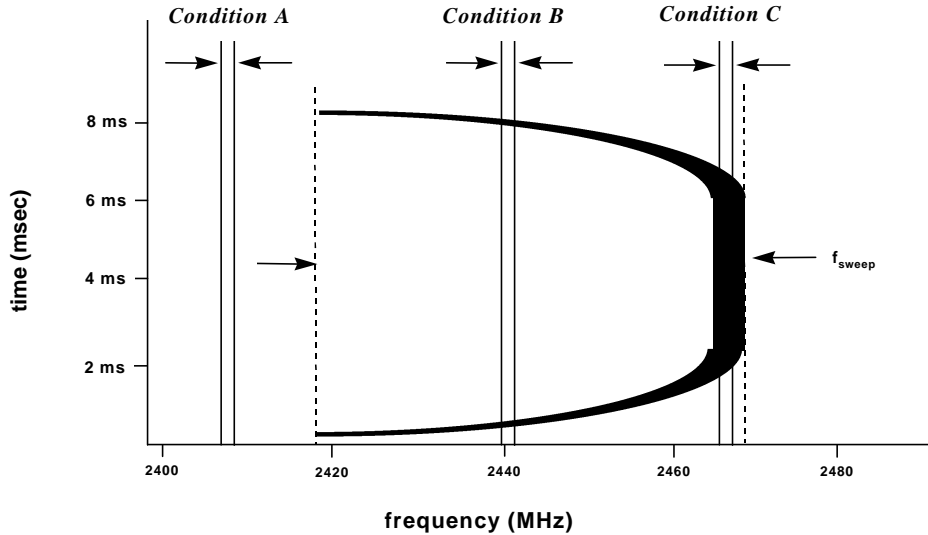
Figure A-1 Possible Conditions for Occupied Channel in Presence of MWO Interference

Condition A: Occupied Channel is Outside Range of Swept Frequency

FCC regulations (15.247) require that all frequencies in the 2.4 GHz be utilized equally. Therefore, the occupied frequency is a uniform random variable in the range of 2.4000 - 2.4835 GHz. Referring to Figure A-1, the probability of occurrence for Condition A (P_A) is given by:

$$P_A \ = \ (83.5 \ \text{MHz} - f_{sweep}) \ / \ 83.5 \ \text{MHz} \qquad\qquad (A.1)$$

It is assumed that transmission is error free in the absence of MWO interference. Therefore, if the occupied channel is outside the range of swept frequency (f_{sweep}) no dropped packets will occur. The packet error rate for Condition A (PER_A) is:

$$PER_A \ = \ 0 \qquad\qquad\qquad\qquad\qquad (A.2)$$

For $f_{sweep} = 50$ MHz:

$$P_A \ = \ (83.5 \ \text{MHz} - 50 \ \text{MHz}) \ / \ 83.5 \ \text{MHz} \ = \ 40.1\%$$

This value establishes an absolute minimum level of system reliability. Regardless of packet length, packets transmitted on channels outside the range of swept frequency will be successfully received.

*Condition B: Occupied Channel is Within Range of Swept Frequency and Experiences
                       Interference on Magnetron Transients*

In this case, successful transmission relies on the ability to transmit packets between bursts of MWO interference. If the packet is longer than the time gap between bursts of interference, successful transmission is not possible. If the packet is shorter than the gap duration as shown in Figure A-2, the start of transmission (t_{start}) must be such that the packet can be completely sent before the next burst.
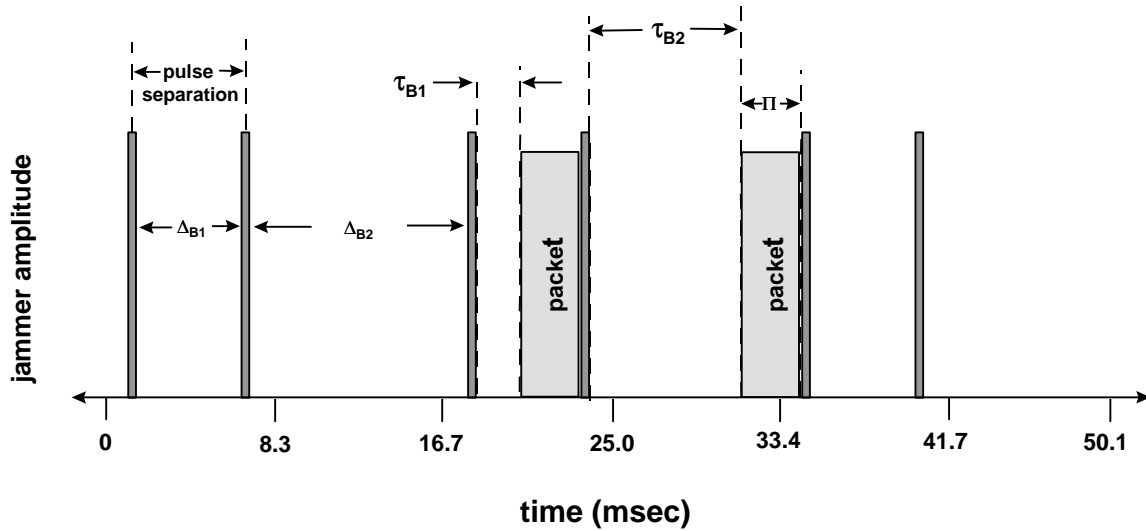
Figure A-2   Time Gaps between MWO Interference Pulses (Condition B)

It is assumed that the bandwidth of emissions from the MWO is about 1 MHz once it reaches steady state operation. The probability of occurrence for Condition B (P_B) is:

$$P_B = (f_{sweep} - 1 \text{ MHz}) / 83.5 \text{ MHz} \qquad (A.2)$$

As shown in Figure A-2, there are two distinct gaps, Δ_{B1} and Δ_{B2}, to consider. The window of starting time for successful transmission for Gap B1 (τ_{B1}) is:

$$\tau_{B1} = \Delta_{B1} - \Pi \qquad (A.3)$$

where:

τ_{B1} = window of start of transmission in Gap B1
Δ_{B1} = Gap B1 duration
Π = packet length (time)

The computation for τ_{B2} is identical. The probability of packer error given that Condition B holds (PER_B), is:

$$PER_B = 1 - [(\tau_{B1} + \tau_{B2}) / 16.7 \text{ msec}] \qquad (A.4)$$

The time gaps vary slightly over the range of swept frequency. However, for the purposes of this model, this effect is neglected. The time gaps, Δ_{B1} and Δ_{B2}, are treated as constants.

Condition C: Occupied Channel Frequency is same as Magnetron Steady State Operating Frequency

The frequency sweeps induced by the off/on and on/off transients of the MWO magnetron are of relatively short duration. After the initial off/on transient, the magnetron frequency achieves steady state and dwells on a particular frequency for about 80% of its duty cycle, or about 6.4 msec, as shown in

Figure A-3. For this period, the MWO looks like a relatively stable narrow band jammer. It is assumed that the MWO jams only a single channel during this time. The probability for Condition C (P_C) is:

$$P_C \quad = 1 \text{ MHz} / 83.5 \text{ MHz} = 0.012 \qquad\qquad (A.5)$$
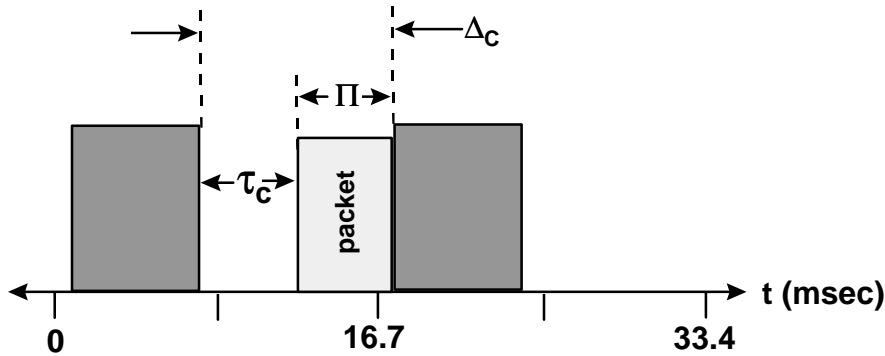
Figure A-3   MWO Interference Pulses (Condition C)

As shown in Figure A-3, there is only a single time gap (Δ_C) to consider. The window of starting time for successful transmission for Gap C (τ_C) is:

$$\tau_C \quad = \Delta_C - \Pi \qquad\qquad (A.5)$$

and the and the probability of packet error for Condition C (PER_C) is:

$$PER_c \quad = 1 - [(\tau_C) / 16.7 \text{ msec}] \qquad\qquad (A.6)$$

Receiver Sensitivity

In order to include the effects of receiver sensitivity, some assumptions about modulation must be made. As described in the main text, 2FSK (h=0.32) and 4FSK (h=0.16) signaling is used. The probability of bit error (P_e) for noncoherent FSK receivers is described by Proakis [7].

In the event that a packet encounters a burst of interference, some number of bits (n) will be corrupted. In this sense, a corrupted bit is one which is transmitted during a burst of interference. It may or may not be received in error. The exact number of corrupted bits is dependent on the packet length (Π), the duration of the interference burst (Ω), and the start-of-transmission time (t) as shown in Figure A-4.
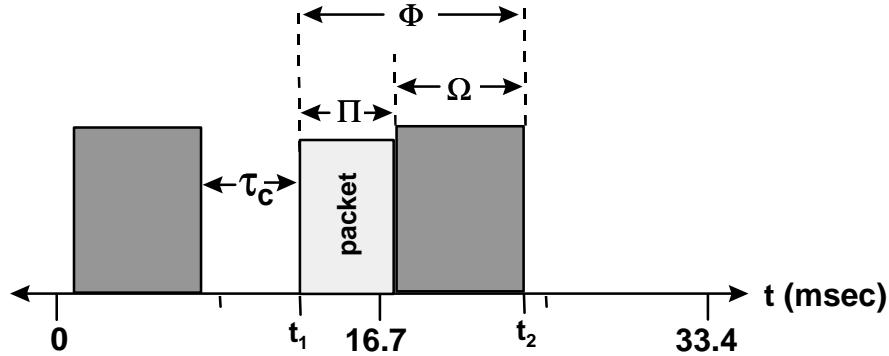
**Figure A-4   Packet in Presence of MWO Burst**

The number of corrupted bits as a function of start-of-transmission time (t) is shown in Figure A-5. This is actually a correlation of the packet and MWO burst. Given that interference occurs, the expected number of corrupted bits (n) is the average value of the correlation function over the interval for which it is non-zero (t_1 to t_2), as in Figure A-6.
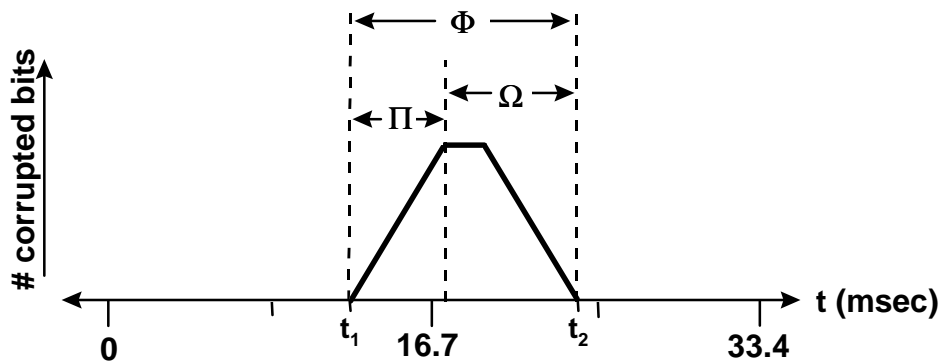
Figure A-5   #Corrupted Bits as Function of Start Time (t)
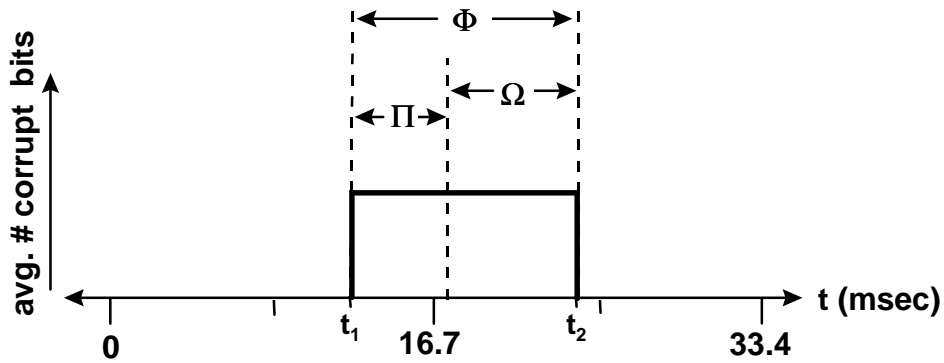
Figure A-6   Average #Corrupted Bits as Function of Start Time (t)

The computation for packer error rate given Condition C (PER_C) is:

$$PER_C = P_C * P_{MWOC} * [1 - (1 - P_e)^n]$$ (A.7)

where:

PER_C = Packet Error Rate given Condition C
P_C = Probability of Condition C
P_{MWOC} = Probability of encountering MWO interference given Condition C
P_e = Probability of bit error
n = estimate of number of corrupted bits

The computation for PER_B is identical to the method shown in (A.7).

Overall Probability of Successful Packet Transmission

Conditions A, B and C are mutually exclusive events. The overall packet error rate is:

$$PER = \{P_A * PER_A\} + \{P_B * PER_B\} + \{P_C * PER_C\}$$ (A.8)