Reliability of IEEE 802.11 Hi Rate DSSS WLANs in a High Density Bluetooth Environment

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Abstract:

The issue of coexistence between IEEE 802.11 high speed Direct Sequence Spread Spectrum (DSSS) and Bluetooth radios with both radio types located within a mixed environment is studied. A network topology, propagation model, and user traffic loads are postulated. The reliability of IEEE 802.11 Hi Rate DSSS radios is then estimated under the stated conditions.

1.0 Introduction

IEEE 802.11 and Bluetooth (BT) radios share common spectrum in the 2.45 GHz ISM band. In addition, both radio types are to a large degree targeted at the business user. With the advent of 11 Mbps data rates, IEEE 802.11 Direct Sequence Spread Spectrum (DSSS) radios can provide a mobile extension to wired networks in large enterprise installations. It can replace wired infrastructure entirely in Small Office / Home Office applications.

At the same time, Bluetooth will become an important asset for the mobile worker and business traveler by servicing a number of applications which include downloading e-mail to a laptop via a cellular telephone, synchronizing palmtop devices, and accessing local printers. It is entirely likely that radios of both types will come in close proximity to each other within the enterprise setting.

In order to determine the degree to which the radios will cause harmful interference to each other, a number of assumptions are necessary. It is difficult, if not impossible, to define a "typical" network topology. User scenarios and even indoor propagation models can be rather subjective. However, by using some reasonable assumptions, analysis of the interference caused by co-location of the two radio types can proceed. Assumptions include:

a. a network topology and user density
b. propagation model
c. network traffic loads for IEEE 802.11 and BT

A high density environment has been postulated. Large numbers of both types of devices are present within the topology analyzed. In addition, traffic loads are assumed for the BT piconets. This paper focuses exclusively on the reliability of the IEEE 802.11 high speed wireless network in the presence of interference from Bluetooth radios. The reverse situation, that being the effect of IEEE 802.11 DSSS radios upon Bluetooth piconets, is not analyzed. It must be emphasized that the results of this analysis should be considered preliminary. Further study is needed to verify key underlying assumptions, including the effective bandwidth over which a Hi Rate DSSS receiver is susceptible to Bluetooth interference.

2.0 Network Topologies

In order to analyze the coexistence issue, a topology for the IEEE 802.11 Wireless LAN (WLAN) and the BT piconets must be postulated. It is assumed that there is one BT piconet co-located with each WLAN node. The WLAN network topology and the distributions of BT piconets are described more fully in the following paragraphs.

2.1 IEEE 802.11 WLAN Topology

In a typical WLAN installation, wireless stations (STAs) are associated with a fixed Access Point (AP) which provides a bridging function to the wired network. The combination of the AP and its associated STAs is referred to as a Basic Service Set (BSS). For the purpose of this analysis, the following assumptions were made:

a. STAs may be located up to 20 meters from the AP
b. The average density with in the BSS is one STA every 25 sq. meters
c. The transmitter power for both STAs and the AP is +20 dBm

Based on the above assumptions, there are 50 STAs associated with the AP. This topology is shown in Figure 2.1-1. The received signal strength is obviously a function of distance from the AP. It will be seen that the degree to which an IEEE 802.11 radio experiences interference is dependent upon its distance from the AP.

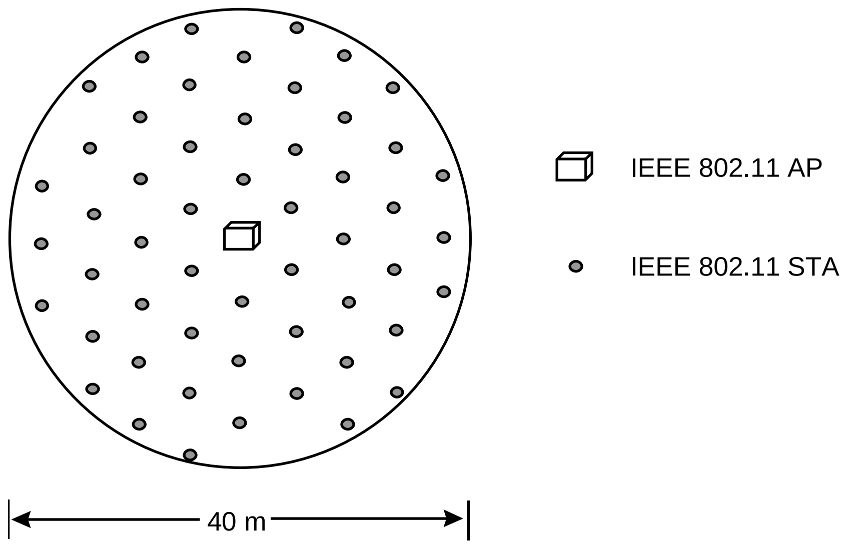

Figure 2.1-1 IEEE 802.11 Enterprise Network Topology

2.2 Bluetooth Topology

For the purpose of this analysis, it is assumed that there is one BT piconet co-located (within the same office or cube) with each IEEE 802.11 STA. The BT piconet consists of two or more BT devices which are capable of establishing at least a point-to-point link. These devices are limited to 0 dBm transmit power. BT equipped devices which might be found in the enterprise include:

a. Desktop PCs
b. Palmtops / laptops
c. Cell phones
d. Local printers
e. Wired phones (interface with BT cell phones or headsets)

In summary, each BT piconet consists of two or more devices capable of establishing at least a point-to-point link. There is one BT piconet co-located with each IEEE 802.11 STA. The resulting composite wireless network topology is shown in Figure 2.2.1. Note that while there are many piconets distributed throughout the area covered by the IEEE 802.11 WLAN, the number of BT piconets which are actively transmitting at any point in time is highly dependent on usage scenarios.

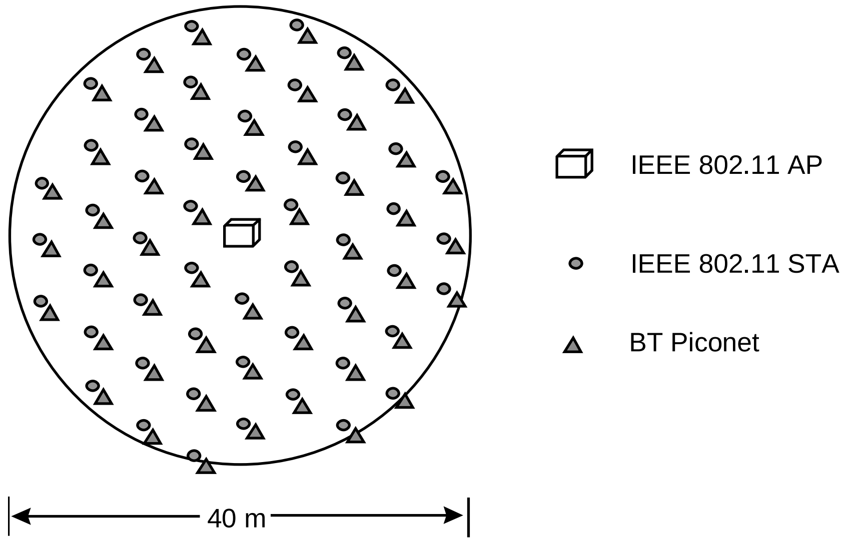

Figure 2.2.1 Composite BT/DSSS Network Topology

3.0 Propagation Model

In order to facilitate analysis, a simplified indoor propagation model has been proposed [3]. Line-of-sight propagation is assumed for the first 8 meters. Beyond this point, path loss (L_{path}) increases as a function of $\mathbf{r}^n$, where **r** is range and n = 3.3. This can be expressed in terms of decibels:

$$L_{path} = 20 \log (4 \pi r / \lambda), \quad r \leq 8 \text{ m} \tag{1}$$

$$= 58.3 + 33 \log (r / 8), \quad r > 8 \text{ m} \tag{2}$$

where:

λ = free space wavelength @ 2.45 GHz (0.1224 m)

r = range (m)

3.1.1 Range of Interference

The degree to which an IEEE 802.11 STA is susceptible to interference from nearby BT transmitters is clearly dependent upon the strength of the desired DSSS signal from the AP. DSSS signal strength is, of course dependent upon range from the AP. Therefore, STAs are more susceptible to BT interference as the range from the AP increases. The effect of BT interference will be examined at three values of range from the AP. Those values are 4, 10 , and 20 meters.

An 11 Mbps DSSS radio can provide reliable service with a narrow band interferor (such as a BT transmitter) falling within its pass band as long as the Signal-to-Interference Ratio (SIR) is greater than roughly 10 dB [3]. This approximation is conservative and has been verified in lab tests. Therefore, if the BT signal is more than 10 dB below the DSSS signal, it will not cause significant interference. However, when the BT interference exceeds the 10 dB SIR threshold, the DSSS STA will experience a dropped packet provided there is an overlap in time and frequency. Therefore, the number of potential BT interferors to which a DSSS node is exposed to depends on the range from the AP.

Example:

Consider the case of a DSSS STA which is located 20 m from the AP. The received signal from the AP is estimated by:

$$\begin{aligned} Prx &= Ptx - Lpath \qquad (3) \\ &= +20\ \text{dBm} - (58.3 + 33 \log (20 / 8)) \\ &= -51.4\ \text{dBm} \end{aligned}$$

Based on the assumption that the DSSS signal must be 10 dB greater than any BT signal to overcome the interference when the BT signal falls in the DSSS passband, the maximum permissible BT signal would be –61.5 dBm. Using the propagation model described in equation (1), this would correspond to a required separation of 10 meters.

Range to AP (m)	**Rx DSSS Signal (dBm)**	**Maximum BT Signal (dBm)**	**Radius of BT Interference (m)**	**Number of BT Interferors in Range**
4	-32.3	-42.3	1.27	1
10	-41.4	-51.4	3.66	2
20	-51.4	-61.4	9.95	13

Table 3.1.1-1 Impact of BT Interference Depends on Range from AP

Therefore, the DSSS STA located 20 meters from the AP would be susceptible to interference from a BT interferor located anywhere within a range of 10 meters. This corresponds to an area of 314 m^2. For the situation under consideration, there is one BT piconet for every 25 m^2 of office space. Therefore, in an area of 314 m^2, there could be as many as 13 BT piconets. The number of BT piconets within range of any given node has been computed as a function of distance from the AP. The results are shown in Table 3.1.1-1.

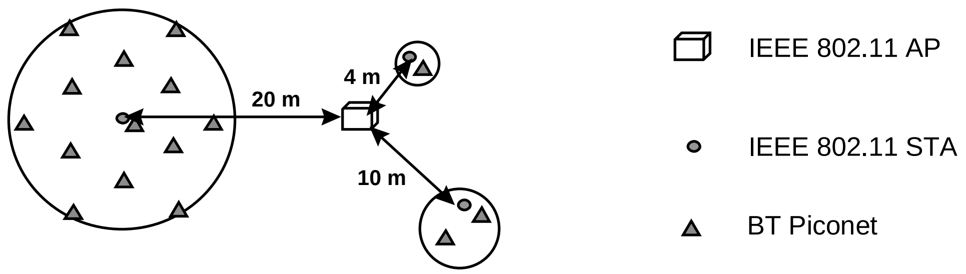

Figure 3.1.1-1 Number of Potential BT Interferors Depends on Range from AP

3.2 Interference Model

A model which predicts the effects of interference from a nearby BT transmitter on an IEEE 802.11 DSSS receiver has been described previously[1,2]. As predicted in the model, even if a nearby BT piconet is active, there is still a significant probability that the DSSS receiver will avoid the interference. For a BT transmission to disrupt a DSSS packet, there must be an overlap in time and in frequency. As shown in Figure 3.2-1, the likelihood of interference depends on the length of the DSSS packet, and the degree to which the BT piconet is loaded.

The analysis presented here is based solely on the use of single time slot packets by the BT piconet. It is assumed that this is the worst case scenario, since the use of multiple time slot packets effectively reduces the BT hop rate and increases throughput. This reduces transmission time and results in longer gaps in BT interference, thereby increasing the chances of successful reception of DSSS packets.

From Figure 3.2-1, it can be seen that a DSSS packet can overlap a number of BT time slots. However, there is only about a 25% probability that an active BT transmitter will be in the DSSS passband on any given hop period. It should also be mentioned that the probability of collision is further reduced by the fact that the BT transmitter is only active for 366 μsec in each 625 μsec dwell period.

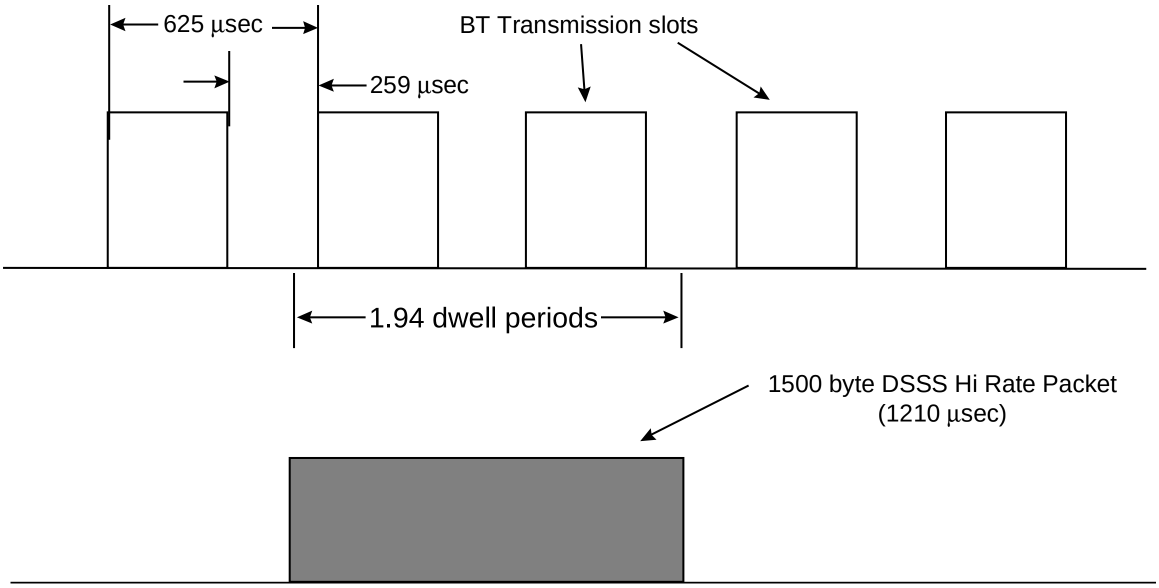

Figure 3.2.1-1 Probability of Collision Depends on Number of BT Slots Overlapped

As it turns out, IEEE802.11 packets are very short in duration. The largest allowable packet size is 1500 bytes (12,000 bits). However, due to the high data rate, the entire packet requires only 1210 μsec to transmit including the packet header and preamble. A DSSS packet of this duration would overlap only two or three BT dwell periods. In the example below, the weighted probability of overlapping either two or three dwell periods is computed. The start of transmission (relative to the BT hop times) is modeled as a uniform random variable.

The load factor of the BT piconet must also be taken into consideration when determining the overall probability of collision. As will be described in greater detail below, support of one full duplex phone conversation within a BT piconet (or point-to-point connection) using an HV3 packet format requires transmission on 33% of the BT time slots.

Example:

Consider reception of a 1500 byte DSSS packet while one nearby BT piconet is supporting a telephone conversation with an HV3 packet format. Full duplex voice requires a system throughput of 128 kbps. Total BT throughput using the HV3 packet format is 386 kbps. This corresponds to a piconet load factor (L_{pico}) of 33%. Therefore, supporting a single voice conversation requires transmission within the piconet on every third time slot.

Assuming the SIR ratio is less than 10 dB, the only means by which interference can be avoided is for the DSSS packet to arrive between BT transmission bursts, or while the BT piconet is actively transmitting on a frequency which does not fall in the DSSS passband. If either condition is violated at any point during the DSSS packet duration, it is assumed an error will occur.

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 625 μsec. Based on these considerations and the piconet load factor, the probability of collision for the single DSSS packet under consideration can be computed:

Probability BT tx hops into DSSS passband (P_{hop}):	25%
Probability of overlapping 2 BT tx slots ($P_{2\text{-}slot}$):	51.5%
Probability of overlapping 3 BT tx slots ($P_{3\text{-}slot}$):	48.5%
Piconet Load Factor (L_{pico}):	33.3%

Probability of collision with n slot overlap ($P_{coll}(n)$)

$$P_{coll}(n) = 1 - (1 - (P_{hop} * L_{pico}))^n = 1 - (0.9175)^n \quad (4)$$

Overall Probability of collision (P_{tot})

$$P_{tot} = (P_{2\text{-}slot} * P_{coll}(2)) + (P_{3\text{-}slot} * P_{coll}(3)) \quad (5)$$

$$= ((0.515 * 0.1582) + (0.485 * 0.2276))$$

$$= 19.2\ \%$$

The foregoing analysis is helpful, but it does not describe the situation completely. Accurate estimates of IEEE 802.11 network throughput in the presence of interference must account for the possibility of BT collisions with ACK packets, and network overhead associated with re-contention for the network in the event the transmitting station fails to receive an ACK. These effects have been included in the computation of the impact of interference from a single BT interferor as a function of packet size (bytes) and BT piconet load. Results are shown in Figure 3.2.1-2.

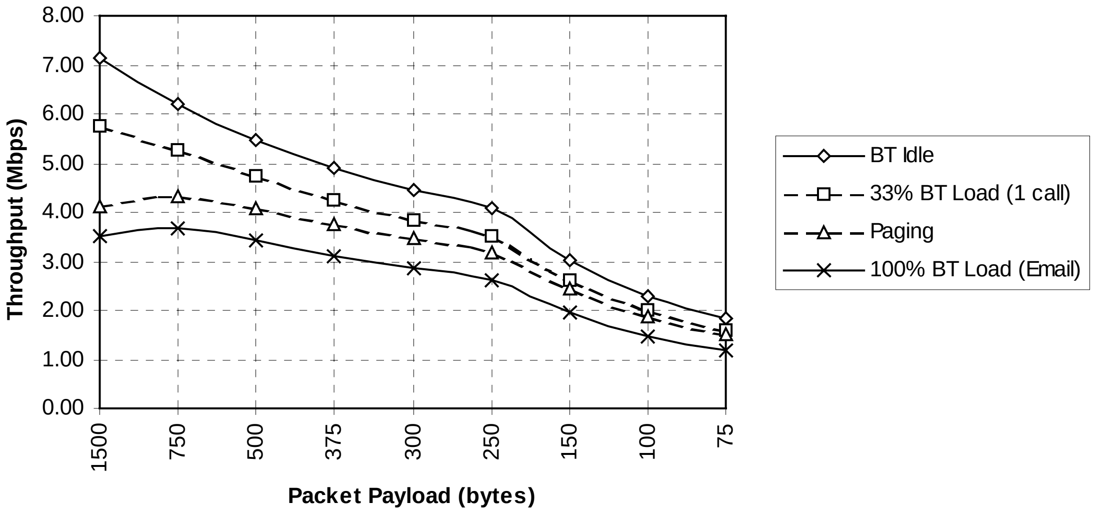

Figure 3.2.1-2 Throughput for DSSS WLAN as a Function of Piconet Utilization (Single BT Interferor)

As discussed in Section 3.1.1 above, there can be multiple BT piconets which are close enough to cause interference in the event the transmitter hops into the DSSS receiver passband during reception of a packet from the AP. Therefore, there is the possibility that multiple piconets could be active simultaneously. For example, if there are ***m*** telephone calls occurring simultaneously, the probability of interference (P_{mult}) from multiple sources of BT interference is approximated by:

$$P_{mult}(m) \quad = \quad 1 - (1 - P_{tot})^m \qquad (6)$$

The probability of activity from one or more interfering transmitters is entirely dependent on the BT user scenarios, which are described in the following section.

4.0 BT User Scenarios

In order to estimate the reliability of the IEEE 802.11 WLAN in the presence of BT interference, user traffic patterns must be postulated. Estimates for typical usage for a BT piconet in an enterprise setting were provided by the Bluetooth SIG and are presented in Table 4.0-1.

Category	Traffic	BT Packet Structure
Paging	1 time / connection	ID
e-mail	15 / day @ 10 kbytes each	DH1
Telephony	10 calls / day @ 1 min. each	HV3

Table 4.0-1 Typical Usage of BT Piconet in Enterprise Environment

4.1 Paging

The quiescent state of all BT nodes is assumed to be the STANDBY mode. It is assumed that each BT node is already aware of the addresses of the other nodes within each piconet. Prior to transmitting data or establishing a telephony connection, the initiating BT node must enter the PAGING mode. Based on the user scenarios described in Table 4.0-1, there will be 25 PAGING periods per day (a day is assumed to be 8 hours) for each BT piconet. PAGING requires an average of 1.3 sec to complete. During PAGING, the BT piconet hops at 3200 hops/sec, and transmits a very short ID packet, which is approximately 70 μsec long. A time profile of the PAGING process is shown in Figure 4.1-1.

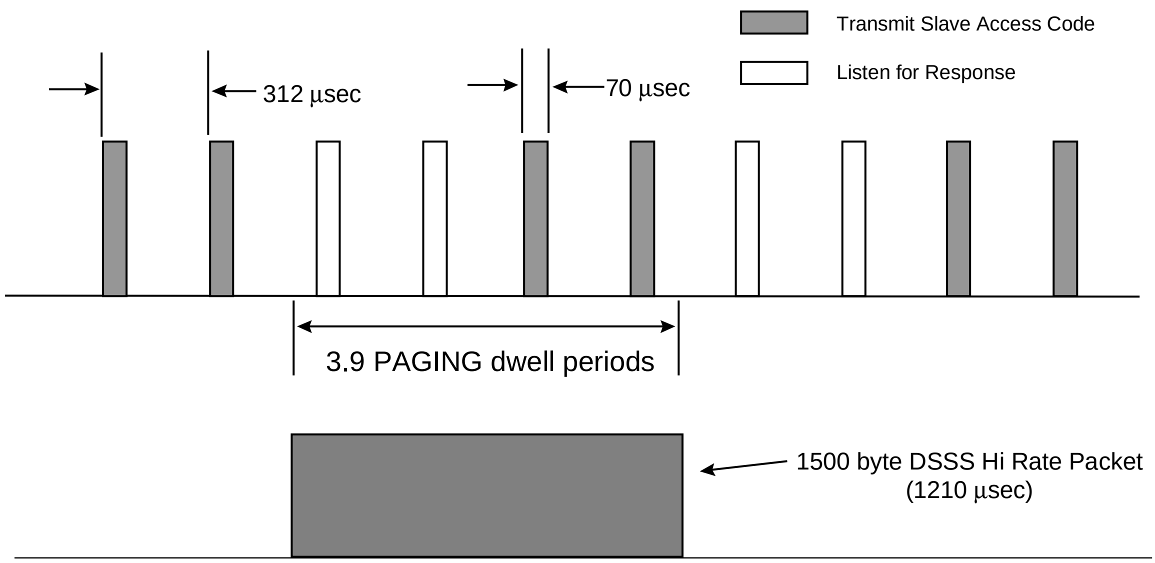

Figure 4.1-1 BT Piconet Hops at 3200 hops/sec While in PAGING Mode

The effect on IEEE 802.11 DSSS throughput due to interference from a single BT piconet in the PAGING mode has been computed and are shown in Figure 4.1-2. PAGING represents a special case due to the rapid hop rate and bursty nature of BT transmissions. While the interference is significant, this situation is mitigated by the fact that a BT piconet spends relatively little time in the PAGING mode. For the user scenarios stated above, a single piconet would spend about 32 seconds per day in this mode. In spite of the severity of this condition, the IEEE 802.11 DSSS WLAN can maintain a *throughput* of about 4 Mbps. The results in Figure 4.1-2 suggest a packet size of 750 bytes is optimal for minimizing the impact on throughput under this condition.

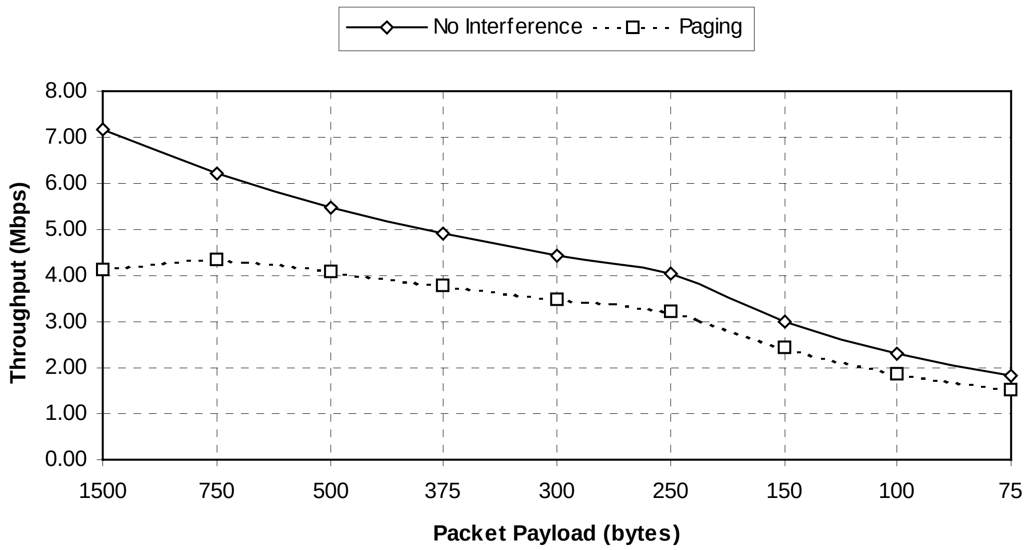

Figure 4.1-2 IEEE 802.11 WLAN Throughput During BT PAGING Procedure

4.2 E-mail Down/Up Loads

The User Scenarios in Table 4.0-1 indicate that about 15 e-mails per day will be uploaded or downloaded via the BT piconet by an enterprise user. Assuming this will be accomplished using the DH1 packet format, the total time an individual BT piconet is in this mode can be computed:

BT Throughput with DH1 packet:	179 kbps
Total daily email traffic per piconet:	150 kBytes (1.2 Mbits)
E-mail down/upload time / day:	6.7 sec / day
BT piconet load factor:	100%

E-mail up/downloads represent a piconet load of 100% during transmission. The effect on IEEE 802.11 DSSS WLAN throughput from interference generated by a fully loaded BT piconet is shown in Figure 3.2.1-2. There is a noticeable effect, but the amount of time spend in this mode is very low (6.7 sec/day) based on the assumed user profile.

4.3 Telephony

The User Scenarios in Table 4.0-1 indicate that an average of 10 phone calls per day will be supported by each BT piconet, each call being 1 minute in duration. Full duplex telephony requires a throughput of 128 kbps. Assuming this will be accomplished using the HV3 packet format, the BT load factor is computed by:

BT Throughput with HV3 packet:	386 kbps
Required throughput for single call:	128 kbps
BT piconet load factor:	33%

The effect on throughput of interference from a single BT piconet operating at 33% load on IEEE 802.11 DSSS WLAN throughput is shown in Figure 3.2.1-2. The result is a reduction of about 19% in throughput while a single phone conversation is in progress.

4.4 Weighted Average Effect of Single BT Interferor

Up to this point, the effects of particular usage modes have been studied in isolation. However, it is of interest to determine the average effect on WLAN reliability of all BT user modes. Such a weighted average accounts not only for the effects of the individual user modes, but accounts for the fraction of time that the BT piconet is in each mode. This gives an idea of the average effect over the course of an 8 hour day. Results are shown in Figure 4.4-1.

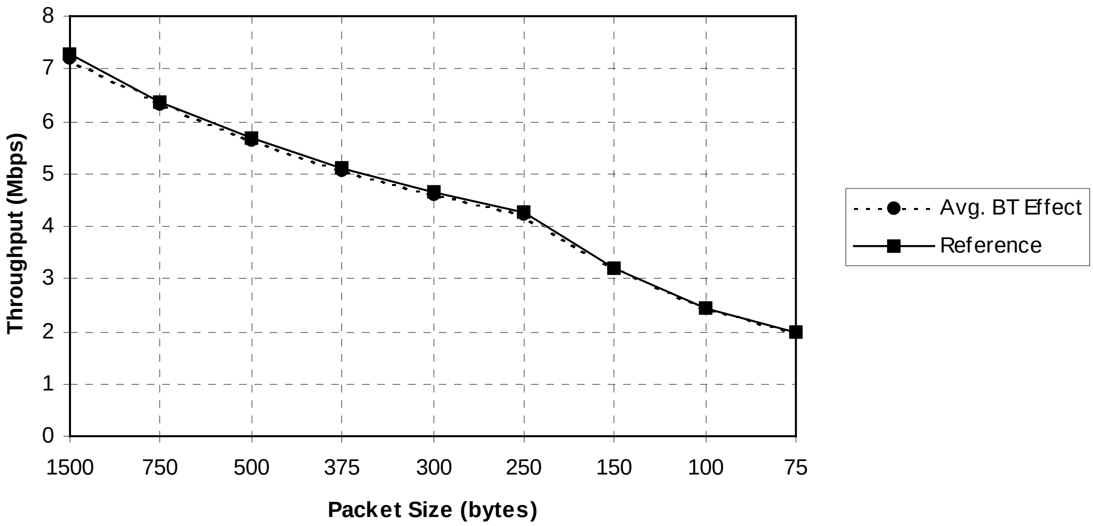

Figure 4.3-1 Average Effect of BT Interference Over an 8 - Hour Day

The "Reference" curve represents IEEE 802.11 network throughput in the absence of BT interference. Note that the two curves are virtually indistinguishable. This is due largely to the fact that the BT user scenarios identified result in activity for only about 15 minutes per day. Figure 4.3-1 shows the effect of a single BT piconet. As discussed earlier, when an IEEE 802.11 DSSS node is located at a significant distance from the AP, it can experience interference from a number of nearby BT piconets. This issue is explored in the following section.

5.0 Interference from Multiple BT Piconets

As shown in Table 3.1.1-1, the range at which a BT transmitter can interfere with a DSSS receiver increases as range between the DSSS receiver and the AP increases. Therefore, in order to estimate the reliability of a 2.45 GHz DSSS WLAN within the network topology described above, the effects of interference from multiple BT piconets must be examined.

	Range = 20 meters	**Range = 10 meters**	**Range = 4 meters**
# Potential BT	**13**	**2**	**1**

Jammers			
BT Idle	74.7%	95.6%	98.8%
1 Call	20.7%	4.1%	2.1%
2 Calls	2.6%	0.04%	---
3 Calls	0.2%	---	---
4 calls	0.01%	---	---
E-mail	0.22%	0.05%	0.02%
Paging	1.1%	0.22%	0.11%
Blocked	0.35%	0.00%	---

Table 5.0-1 Estimated Likelihood of Various BT Interference Conditions

The worst case is clearly that of a DSSS receiver located 20 meters from the AP. In this situation, the DSSS receiver is susceptible to interference from any BT piconet which is located with 10 meters. For the topology studied, this translates into approximately 13 BT piconets. At this range from the AP, there is a greater possibility of receiving interference from multiple BT transmitters simultaneously.

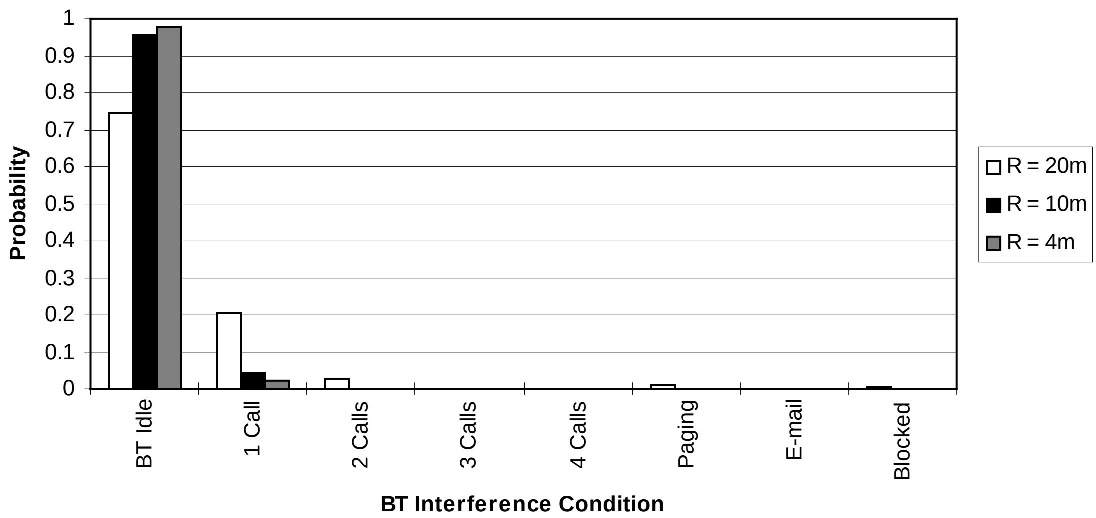

Figure 5.0-1 BT Interference is Dependent on Range from AP

Table 5.0-1 shows the probability of various levels of BT interference conditions as a function of distance from the AP. Note that as distance increases, there is an increasing possibility that the DSSS receiver will be exposed to interference from multiple simultaneous BT phone calls. There is also some possibility that at maximum separation from the AP, the DSSS receiver can experience very brief periods of complete blockage when one BT piconet is in the process of Paging and one or more telephone calls are in progress on a different nearby BT piconet.

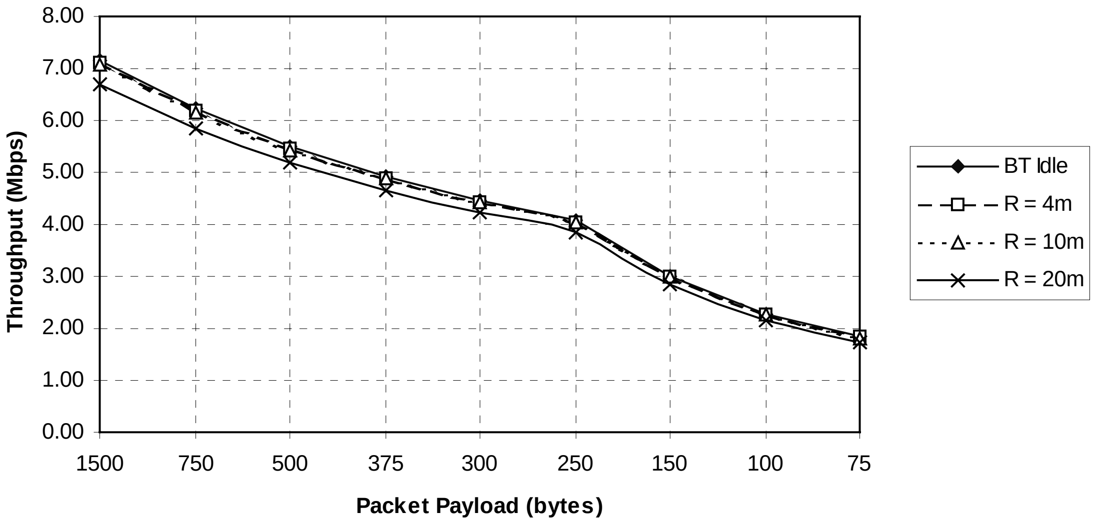

Figure 5.0-2 IEEE 802.11 DSSS WLAN Average Throughput in Presence of BT Interference at Various Ranges from AP

Figure 5.0-2 shows a plot of estimated average IEEE 802.11 WLAN throughput under the stated conditions. It is worth noting that even under extreme conditions, use of larger packets (750 - 1500 bytes) can sustain throughput of 4 Mbps or better. It is should also be pointed out that these are average numbers. Instantaneous throughput can be much better if nearby BT piconets are idle, or it can be worse if BT activity temporarily peaks. Figures 5.0-3, 5.0-4, and 5.0-5 show availability curves for IEEE 802.11 WLAN service under the stated conditions at distances from the AP of 4, 10, and 20 meters.

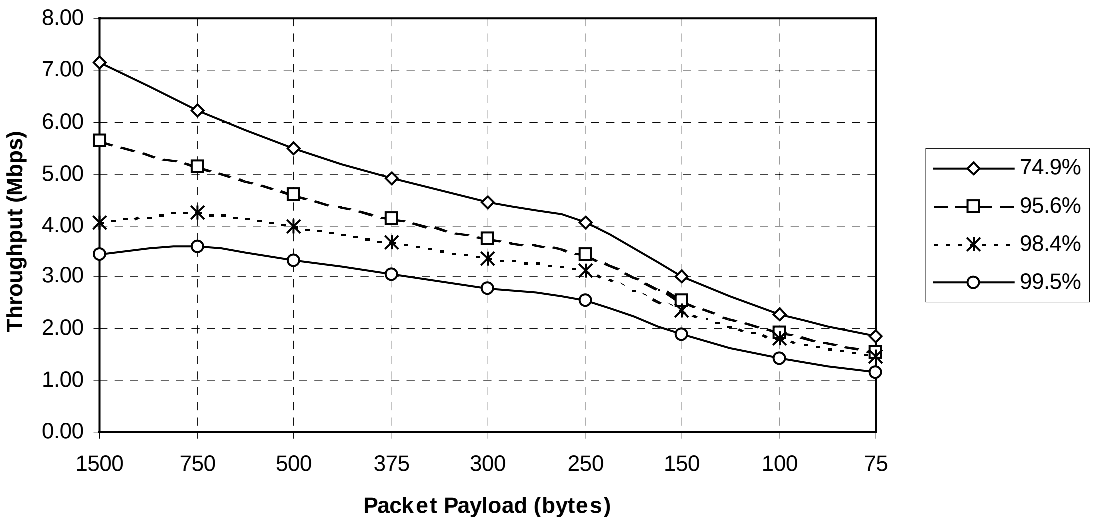

Figure 5.0-3 Availability Curve for IEEE802.11 WLAN in Presence of BT Interference (Range to AP = 20 m)

The results in Figure 5.0-3 indicate that throughput will be 5 Mbps or greater 95.6% of the time with range to the AP at 20m. The lower curve (99.5%) shows the effects of a nearby BT piconet downloading email via using a DH1 packet, which results in a 100% BT load factor.

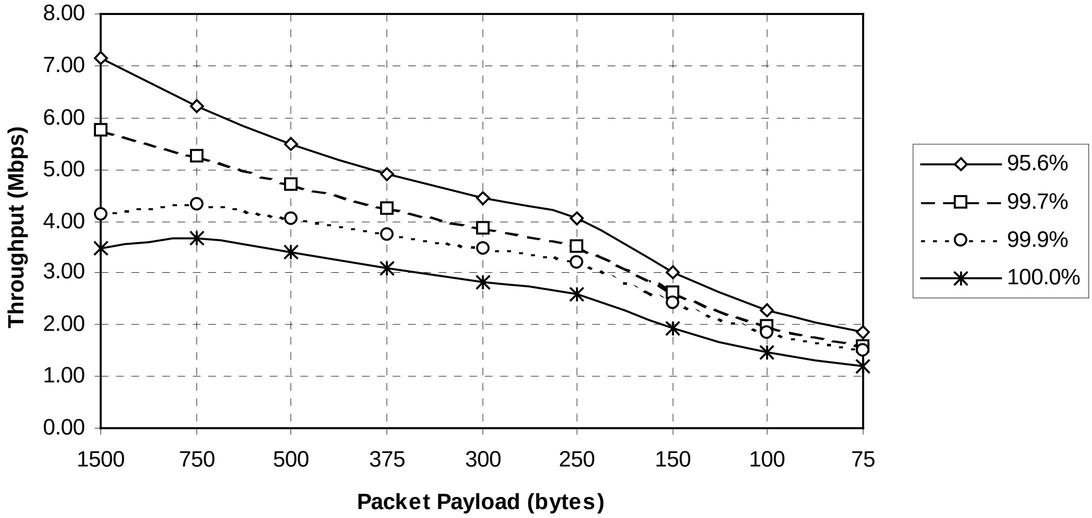

Figure 5.0-4 Availability Curve for IEEE802.11 WLAN in Presence of BT Interference (Range to AP = 10 m)

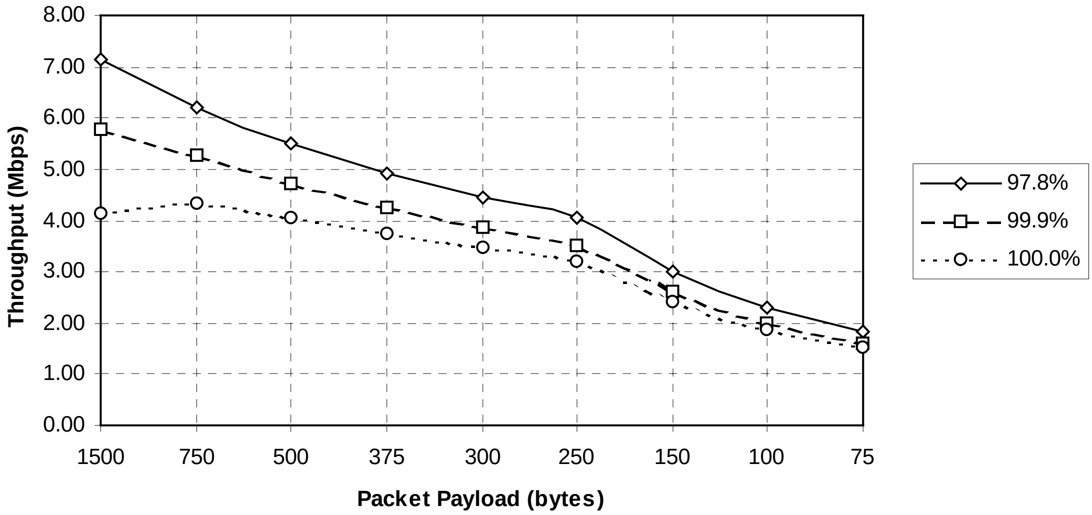

Figure 5.0-5 Availability Curve for IEEE802.11 WLAN in Presence of BT Interference (Range to AP = 4 m)

Figures 5.0-4 and 5.0-5 show that the interference problem is much less severe as range to the AP decreases. The desired DSSS signal is much stronger at shorter distances from the AP and can overcome the effects of BT interference with much higher probability. Maximum throughput (> 7 Mbps) can be maintained 95.6% of the time at 10 m and 97.8% of the time at 4 m.

6.0 Conclusions

This paper has focused on the effects of BT interference on IEEE 802.11 wireless LANs. A model has been described which provides a means of estimating the degree of interference inflicted on an IEEE 802.11 WLAN by a number of BT piconets operating in close proximity. Further work which includes lab testing with DSSS and BT radios operating in close proximity is required. However, some preliminary conclusions can be drawn from the foregoing analysis:

1.) The degree of interference experienced in any installation is dependent on local propagation conditions, the density of BT piconets, and BT piconet loading.
2.) IEEE 802.11 DSSS WLAN susceptibility to BT interference increases as a function of range from the DSSS wireless node to the DSSS AP
3.) IEEE 802.11 DSSS Hi Rate systems show graceful degradation in the presence of significant levels of BT interference
4.) Based on the utilization models studied, IEEE 802.11 High Speed WLANs show good reliability even in a fairly dense environment of BT piconets.

References

[1] G. Ennis, "*Impact of Bluetooth on 802.11 Direct Sequence Wireless LANs*", Doc.: IEEE802.11-98/319a, Sept. 1998.

[2] J. Zyren, "*Extension of Bluetooth and 802.11 Direct Sequence Interference Model*", Doc.: IEEE 802.11-98/378, Nov. 1998.

[3] A. Kamerman, "*Coexistence between Bluetooth and IEEE 802.11 CCK Solutions to Avoid Mutual Interference*", Lucent Technologies Bell Laboratories, Jan. 1999.