

# Performance Analysis of 802.11b Networks in the Presence of Interference-Aware Bluetooth Devices

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## ABSTRACT

IEEE 802.11b Wireless Local Area Networks (WLAN) and Bluetooth Wireless Personal Area Networks (WPAN) provide complimentary services using the same unlicensed radio frequency band of operation. As the benefits of utilizing these services become increasingly apparent, the likelihood of mutual interference may also increase. In this paper an algorithm called Interference-Aware Adaptive Frequency Hopping (IAFH) is proposed and implemented on Bluetooth devices to mitigate the interference between WLAN and WPAN. An analytical channel model of IAFH based on the standard path loss-log normal shadowing-AWGN and Rayleigh multi-path fading channel model is developed to evaluate the performance of the 802.11b devices in the presence of Bluetooth devices. Numerical analysis of the model is done in MATLAB to calculate the throughput of the system using the existing algorithms and the proposed algorithm and the results are compared.

## Categories and Subject Descriptors

C.4 [Performance of Systems]: Performance attributes; C.2.3 [Computer-Communication Networks]: Network Operations—*Network management.*

## General Terms

Algorithms, Performance, Management, Measurement

## Keywords

802.11b, Bluetooth, frequency hopping, coexisting, interference

## 1. INTRODUCTION

IEEE 802.11b Wireless Local Area Networks (WLAN) and Bluetooth Wireless Personal Area Networks (WPAN) provide complimentary services using the same unlicensed radio frequency band. Thus performance degradation is observed when

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they operate in close vicinity [9]. Researchers have tried to study the coexistence through all possible approaches of study: empirical study, mathematical analysis, and simulations [1,10]. In BT-specifications version 2.0, BT Special Interest Group (SIG) introduced Adaptive Frequency Hopping (AFH) as a possible solution to mitigate the problem of interference between 2.4 GHz ISM band devices [14]. After its introduction, researchers started to venture into the problem of AFH for other ways of improvement [5, 10, 12]. However AFH would be ideal only in a slow changing environment where the same sequence could be used for a long period of time. In addition, a need for studying the mathematical model from the perspective of interference and AFH has been ignored by the research community in the past.

In this paper a mathematical model for the interference of 802.11b and Interference-Aware Adaptive Frequency Hopping (IAFH) enabled Bluetooth devices in an indoor environment is presented. In this model, AFH is appropriately combined with the Bluetooth Interference Aware Scheduling (BIAS) technique presented in [2]. An overall mathematical model is developed. The coexistence model is developed to capture the performance impact of Bluetooth interference on the IEEE 802.11b packet reception. Various measures of performance are calculated. Based on the probability of collision and expected number of interferers, the packet error rate is calculated. From all these parameters an expression for throughput of the 802.11b WLAN system in the presence of interfering Bluetooth Piconets is derived.

The rest of the paper is organized as follows. Section II introduces the modulation techniques used in 802.11b and Bluetooth, and discusses the BIAS and AFH techniques. Section III presents the new Interference-Aware Adaptive Frequency Hopping (IAFH) algorithm and its implementation. The analytical models for AFH and IAFH are also derived in Section III. Section IV provides the simulations and the numerical analysis. Finally, the paper is concluded in section V.

## 2. RELATED WORK

### 2.1 Overview of 802.11b and Bluetooth

WPAN is distinguished from other types of wireless networks in both size and scope. Communications in WPAN are normally confined to 10 meters in all directions and offer a speed up to 700 Kbps [3]. This is in contrast to WLAN employing the IEEE 802.11 specifications that typically cover a moderately sized

geographic area such as a single building or campus and offers speeds up to 11 Mbps [3, 13]. The 802.11 standard uses a Direct Sequence Spread Spectrum technology and its processing gain is just over 10 dB. 802.11b uses Complementary Code Keying (CCK) to obtain its higher data rates. The available bandwidth is divided in to channels for the operation of DSSS [3, 5]. Each channel occupies approximately 20 MHz. There are 11 channels identified for DSSS system in the US. The ISM band will accommodate three non-overlapping channels including a total bandwidth of 83.5 MHz [3]. Bluetooth devices, which operates in an ad hoc fashion uses Frequency Hopping Spread Spectrum (FHSS) in the 2.4 GHz band [1]. The network is termed a Piconet. The channel is divided into 625 millisecond intervals, called slots, where a different hop frequency is used for each slot [14]. The device, which initiates communication, is called a master and the other devices are called slaves. As shown in Fig. 1, the master transmission starts in even-numbered slots, while the slave transmission starts in odd-numbered slots. Using FHSS reduces the possibility of interference, where the 2.4 GHz band is segmented into 79 channels, each 1 MHz wide, and each Piconet under control of its master hops from channel to channel. With a symbol rate of 1 Mbps, a Bluetooth slot can carry up to 625 bits since the size of the slot is 625  $\mu$ sec. However, the whole slot is not used for packet transmissions. To allow the transmitter and receiver devices to change from receiver to transmitter mode and make the frequency synthesizer tune to the next channel frequency, a 259  $\mu$ sec turn around time is left at the end of the last slot [6]. Packets can be 1, 3 and 5 slots long, namely DH1, DH3 and DH5, respectively, and are transmitted in consecutive slots [5].

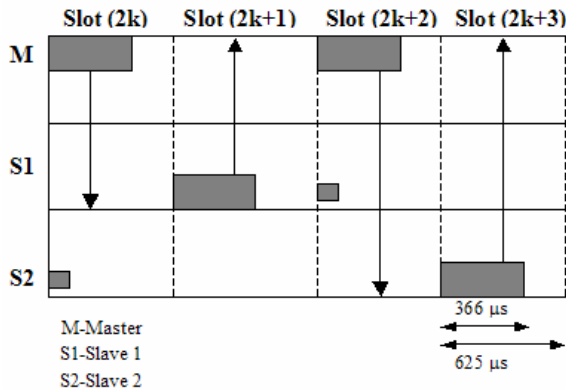


Figure 1: Bluetooth Communication in Multi-slave Operation.

## 2.2 Bluetooth Interference Aware Scheduling

The Bluetooth Interference-Aware Scheduling (BIAS) algorithm is a delay policy implemented at the master device where in the master continuously classifies each frequency as either *bad* or *good* based on a predefined criterion (e.g., a packet loss threshold) [2, 7]. If the frequency is classified as bad, it means that the slot associated with that particular frequency is occupied and Bluetooth cannot transmit. If the slot is good it means that the channel is free and Bluetooth can transmit. Given a master/slave slot pair and their associated frequencies, the master transmits in a slot after it verifies that both the slave's receiving frequency and its own receiving frequency are good. Thus, the master avoids

receiving data on a bad frequency, by avoiding a transmission on a frequency preceding a bad one in the hopping pattern. If either frequency in the pair is bad, the master skips the current transmission slot and repeats the procedure again in the next transmission opportunity. By implementing the delay policy, the channel efficiency and throughput of the system can be maximized considerably but the delay in the packet reception is to be tolerated. BIAS is suitable when the hopping pattern of the Bluetooth changes rapidly. This happens when interference levels change frequently.

## 2.3 Adaptive Frequency Hopping

The first step of adaptive frequency hopping (AFH) is to determine the frequency carrier for each packet, which is determined based on the hop frequency selection scheme. First, a partition hopping sequence is generated and the Bluetooth hops according to this sequence. A new partition sequence is then generated based on the channel classification as good or bad. This newly generated sequence is compared with the original partition hopping sequence. The adapted hop frequency is generated after the checking of a re-mapping function [2, 7]. By implementing this mechanism, the packet transmission is not delayed, but the throughput may decrease and some bad channels are also used. With changing channel conditions the channels are periodically reevaluated and new adapted hop sequences are generated. The basic channel hopping sequence has 79 channels while the adapted sequence may have minimum of 20 channels [5].

## 3. THE NEW IAFH ALGORITHM

### 3.1 IAFH Algorithm

The proposed Interference-Aware Adaptive Frequency Hopping (IAFH) algorithm is devised in order to modify the original Bluetooth frequency-hopping scheme. It is incorporated into the Bluetooth without any modification to the current slot structure.

The algorithm is implemented as follows. A small period of time from the idle 259  $\mu$ sec is chosen to keep sensing the channel for a good frequency slot. If the slot is bad, the master implements a delay policy and it withholds the transmission of the packet. The transmission is postponed until a slot associated with a good frequency becomes available. The master device uses information about the state of the channel in order to avoid data transmission with a bad frequency. Since a slave transmission always follows a master transmission, the master avoids receiving data on a bad frequency by avoiding a transmission on a frequency preceding a bad one in the hopping pattern. The delay policy is implemented till a certain amount of time and if the interference persists for a longer period, then the frequency hopping sequence is modified to replace the bad frequencies using AFH technique. Thus the delay policy could be used when the environment changes quickly and AFH could be used if the interference persists for a long interval of time and same sequence is to be used for a longer period of time. So with the proposed algorithm, the performance can be improved, as no bad channels will be used till a certain point of time and only when the delay becomes unacceptable, the bad channels are used to comply with the Bluetooth transmission rate. The algorithm can be summarized as follows.

## Notations

$d$	delay
$d_{accept}$	acceptable value of the delay
$S_f$	length of the transmission slot using frequency $f$
$l$	length of the packet from master to slave
$N_b$	number of bad frequencies
$N_{b\_min}$	number of bad frequencies that must be used to comply with the Bluetooth transmission rate
$A_{data}$	number of good frequencies

## IAFH Algorithm

```

if  $d \leq d_{accept}$ 
{
  for every even slot of length  $S_f$ 
    // Master transmits on frequency  $f$ 
  check if  $S_f + l$  is good // i.e., "available"
    // Master can receive in next slot
   $A_{data} = \{\text{set of slaves s.t. (good } f)\}$ 
    // Update the slaves frequency status table and fetch
    the
    array with good frequencies
  if ( $A_{data} \neq \text{null}$ )
    select slave  $i$  //According to a priority criteria
    transmit data packet to slave  $i$ 
}
else
{
  initialize the hopping algorithm window size  $S$ 
  increase  $S$  by the number of bad frequencies  $N_b$ 
  if ( $S > 79$ )
    limit to the list size to 79
  else
    choose  $N_b = \min(N_b, 79 - N_{b\_min})$ 
    //use at least  $N_{b\_min}$  different frequencies
}

```

## 3.2 Interference Analysis and Analytical Model

Interference occurs when there is a collision of a packet from the interfering network with the desired signal and the interfering signal has sufficient power to cause errors in recovering the signal. The analysis is centered on deriving a closed form solution for the probability of collision  $P_c$  in terms of radio and network parameters. A collision occurs when one or more interfering signals overlap in both time and frequency with the desired signal. This will lead to a retransmission of the desired signal or a packet. Based on the probability of collision, the packet error rate can be calculated. In the proposed algorithm, the probability of collision is negligible as the packet transmission is withdrawn initially until the slot associated with a good frequency becomes available. During this time, the Bluetooth devices use a small period of time to keep sensing the channel for a good slot. This time is called the Bluetooth sense time and this process continues till a certain amount of time. Therefore even in this case, there will be an overlap in the time domain, which will result in a small collision. The value depends on how large the Bluetooth sensing window time is.

As mentioned earlier, 802.11b consists of three non-overlapping channels with a bandwidth of 22 MHz each. Thus if the 802.11b is transmitting, the Bluetooth may hop in the following number of channels:

$$C = 79 - 22x \quad (1)$$

where  $x$  is the number of 802.11b channels that are transmitting and it can take 1, 2, or 3.

When the available channels for Bluetooth to hop over are more than  $N_{b\_min}$ , it is said to be operating in Mode L, otherwise in Mode H [12].

While these two devices are operating in close vicinity, three possible scenarios can be considered for interference analysis.

- 1) When 802.11b is transmitting in only one channel then Bluetooth devices can operate in all other channels as it has many good available channels in which it can transmit and thus probability of collision with 802.11b devices is negligible.
- 2) When the 802.11b devices occupy two of the available three channels, the Bluetooth devices are left with 35 ( $79 - 44 = 35$ ) channels to transmit and the possibility of collision with 802.11b packets is reduced to a negligible value because it may use the set of minimum number of 20 channels. In this case one thing can be noticed that in worst case, if ( $35 - 20 = 15$ ) channels get corrupted by other sources.
- 3) When all 802.11b bands are transmitting, there is a high chance of collision as the probability of bad channels falling in 802.11b bands increases. This is because only when the 802.11b uses 66 channels out of the 79 channels, only 13 channels are left for Bluetooth devices and they have to use some bad channels from 802.11b band of channels. At least seven bad channels have to be used in this case since the minimum set of 20. Scenarios 1) and 2) fall under Mode-L category, and scenario 3) falls under Mode-H category.

Bluetooth packets have to use some of the bad channels, thus the probability of collision due to Bluetooth on 802.11b at MAC layer is given by the collision in both time and frequency.

$$P_c = P_c(\text{time overlap}) \cdot P_c(\text{frequency overlap}) \quad (2)$$

The packet withdrawal probability is the probability of the sense window overlap with the packet transmission from 802.11b device. In other words it is the probability of collision of the Bluetooth sense window with the 802.11b packet. Therefore, the packet withdrawal probability can be written as:

$$P_w = \frac{802.11b \text{ frame transmission time} + \text{Bluetooth sense time}}{\text{Total Bluetooth time interval}} \cdot \frac{N_b}{N_{b\_min}} \quad (3)$$

Similarly the probability of collision can be written as:

$$P_c = \frac{802.11b \text{ frame transmission time} + \text{Bluetooth occupied time}}{\text{Total Bluetooth time interval}} \cdot \frac{N_b}{N_{b\_min}} \quad (4)$$

Here  $N_B$  is the number of bad channels.

The total bit error probability for CCK modulation at the 802.11b receiver in AWGN in multi path channel using Rayleigh model is given as an approximation as given in [11].

$$P_e = \frac{M}{2M-1} \left( \sum_{m=1}^{M-1} \frac{(-1)^{m+1} \cdot \binom{M-1}{m}}{1+m+m8\Gamma_1} \right) \quad (5)$$

where  $M$  is the number of bits in the symbol and

$$\Gamma_1 = \sqrt{\frac{2E_b}{N_{0total}}}, \quad \text{for CCK}_{11Mbps} \quad (6)$$

where  $E_B$  is the 802.11b signal power, and  $N_{0total}$  is the Noise spectral density.

The probability of packet error determines if the packet must be retransmitted, as the receiver may not be able to decode. When the packets are withdrawn the probability of withdrawal  $P_w$  is derived as:

$$PER = 1 - [(1 - P_e\{no BT\})^{bits \text{ in } 625\mu s} \cdot (1 - P_w) + (1 - P_e\{BT\})^{bits \text{ in } 366\mu s} \cdot (1 - P_e\{no BT\})^{bits \text{ in } 259\mu s} \cdot P_w]^k \quad (7)$$

Similarly, the expression for the packet error rate can be derived, when the packets are collided while implementing AFH. Instead of  $P_w$ ,  $P_c$  is substituted in all the above equations. The packet error will then be

$$PER = 1 - [(1 - P_e\{no BT\})^{bits \text{ in } 625\mu s} \cdot (1 - P_c) + (1 - P_e\{BT\})^{bits \text{ in } 366\mu s} \cdot (1 - P_e\{no BT\})^{bits \text{ in } 259\mu s} \cdot P_c]^k \quad (8)$$

where,  $k = \frac{T_{w,t}}{T_{BT,slot}} = \frac{T_{w,t}}{625\mu s}$  and  $T_{w,t}$  is the 802.11b packet transmission time.

For multiple Piconets in the vicinity of 802.11b station, the number of Piconets or effective number of interferers is given in [4, 8, 14].

The channel model under consideration has been assumed to be lognormal shadow model in which the signal power and interference power are based on a standard exponential delay path loss model with path loss exponent  $n$ , and with lognormal shadowing with standard deviation,  $\sigma_{l/s}$ . By letting  $D \rightarrow \infty$ , the expected number of interferers can be solved as given in [4,14] by

$$N(\gamma) = D_{BT} (\pi d_s^2) \exp \left[ \frac{2(\sigma_{l/s}^2 - 10n\Gamma \log_{10}(e))}{(10n \log_{10}(e))^2} \right] \quad (9)$$

where  $D_{BT}$  is the Bluetooth Piconet density. It is the number of Bluetooth Piconets present in a fixed area where the 802.11b station and AP are present.

Packet error rate for multiple Piconets can be written as:

$$PER\{N(\gamma)\} = 1 - (1 - PER)^{N(\gamma)} \quad (10)$$

Throughput is the ratio of the number of bits successfully received to the time taken in transmitting the bits over the medium. The throughput of the 802.11b system in the presence  $N(\gamma)$  Piconets can be written as:

$$T = \frac{Data_{WLAN}}{T_{wt}} (1 - PER)^{N(\gamma)} \quad (11)$$

where  $Data_{WLAN}$  is the data rate at which the 802.11b is transmitted.

In the proposed IAFH algorithm, Equations (3) and (7) are used to calculate the throughput as given in Equation (11) initially when the packets are withdrawn and Equations (4) and (8) are used to calculate the throughput after some time. This will improve the performance of the 802.11b system as no bad channels will be used till a certain point of time and only when the delay becomes unacceptable, the bad channels are used.

## 4. SIMULATIONS AND ANALYSIS

We now present the simulations conducted in MATLAB. The probability of collision is calculated by using Equations (3) and (4). The packet error rate is calculated from Equations (7) and (8). The expected number of Bluetooth interferers is calculated from equation (9) and finally the throughput is calculated from the equation (11).

Fig. 2 shows the plot of probability of collision of the 802.11b packet with respect to number of Bluetooth Piconets. The Bluetooth packet is of DH3 type. The size of the 802.11b packet is 1000 bytes. Bluetooth sense time is 50  $\mu$ sec. A collision occurs only when the 802.11b station is using all the three channels and hence only Mode-H is analyzed.

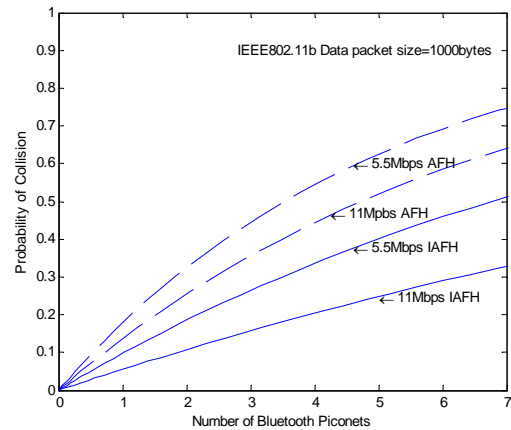


Figure2: Probability of collision with increasing number of Bluetooth Piconets with AFH and the proposed IAFH algorithm.

It can be seen that with the proposed IAFH algorithm, the probability of collision is reduced considerably when compared to AFH. This is because of the transmission of the Bluetooth packets is withdrawn initially and then the hopping sequence is modified. It can also be concluded that the probability of collision is low when the data rate is 11Mbps due to greater transmission rate.

Figure 3 shows the IEEE 802.11b packet error rate in the presence of  $N_i$  interfering Bluetooth Piconets. It compares the results between normal Frequency Hopping (FH), AFH, and IAFH. It is assumed that the probability of packet error was only caused by the channel noise and interference collision.  $P_e(no BT)$  and  $P_e(BT)$  considered here are 0.0001 and 0.5, respectively. The packet error rate is very high even if there exists a single Bluetooth Piconet when FH is used. This is because the packet error rate is dependent in the probability of collision. As the collision is increasing the packet error rate also goes higher. Using AFH reduces the packet error rate and it is still reduced when IAFH is used.

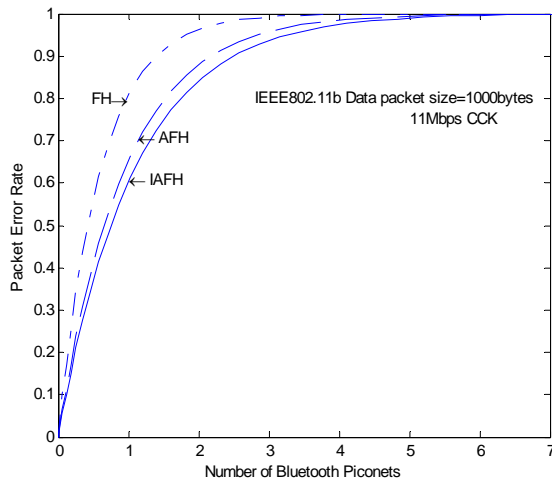


Figure 3: Packet error rate of 802.11b at 11 Mbps.

The effect of distance between the 802.11b transmitting station and the access point is extremely important in the interference analysis. This is because as the distance between the 802.11b station (STA) and the access point (AP) increases, more number of Bluetooth Piconets are likely to be present in between and they may cause interference. Figure 4 shows how the throughput is affected when the distance between STA and AP is increasing.

From Figure 4 one can observe that as the distance between the 802.11b transmitting station and the access point is increasing, the throughput is decreasing very rapidly. With the proposed algorithm, the results are better when compared to normal FH and AFH.

Figure 5 shows the throughput of IEEE 802.11b network when the number of Bluetooth Piconets are increasing and when FH, AFH and IAFH algorithms are applied on the BT devices. With the increase of the number of Bluetooth Piconets, due to the increase

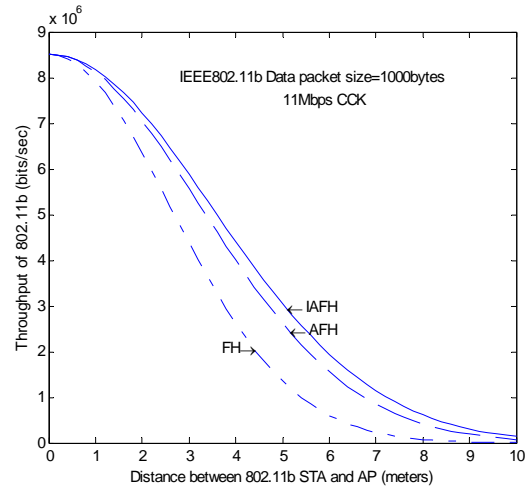


Figure 4: Throughput of the 802.11b system at 11 Mbps in the presence of four BT Piconets.

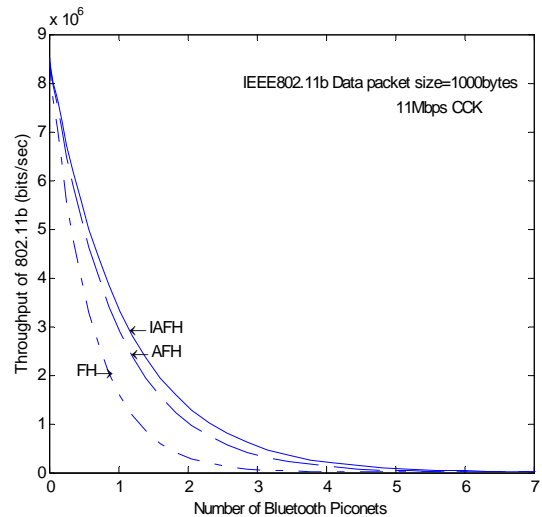


Figure 5: Throughput of 802.11b network using 11 Mbps CCK.

packet error probability in log normal-Rayleigh fading channel model, the throughput of the system decays very fast when the BT devices have to select channels from 802.11b band. The decay is more rapid in the case of FH and it improves with AFH and the proposed IAFH algorithm.

When all the 802.11b stations are transmitting, Bluetooth devices use minimum seven bad channels to transmit without causing significant delay. But if the Bluetooth devices have more data to transmit or more number of Bluetooth Piconets have to transmit, the number of bad channels will increase. Therefore it is important to analyze the performance of the 802.11b system when the bad channels increase.

Figure 6 illustrates that with the increase in the number of bad channels, the packet error rate goes higher.

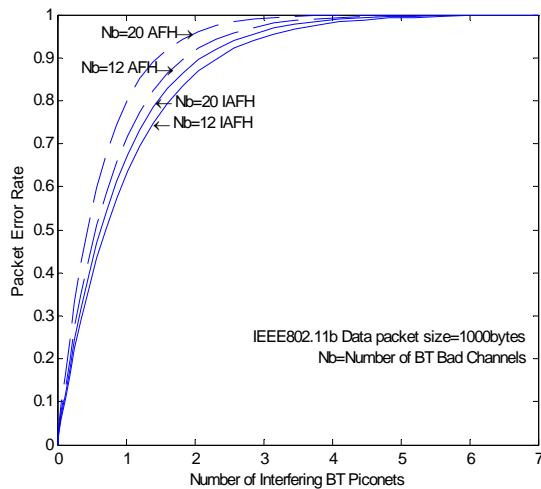


Figure 6: Packet error rate with increased number of bad channels.

Figure 7 shows the plot of the throughput vs. distance between the 802.11b STA and AP with increasing number of bad channels. It can be seen that with the proposed algorithm, the decay in the throughput is not as fast as AFH.

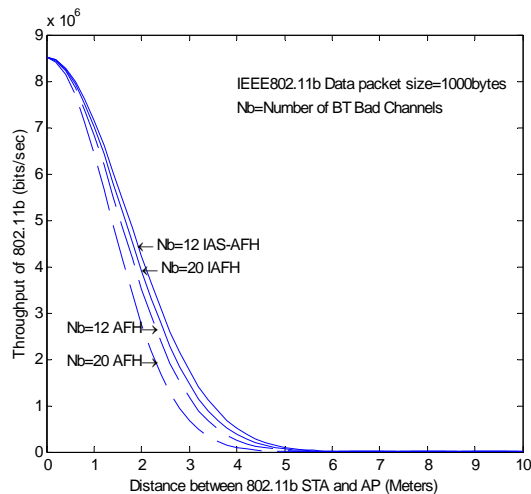


Figure 7: Throughput vs. Distance.

Fig. 8 shows the throughput of 802.11b network in the presence of Bluetooth Piconets with AFH and IAFH implemented. With the increase in the number of Bluetooth Piconets, due to the increase in the packet error probability in the channel model, the throughput decays very fast when Bluetooth devices have to select channels from 802.11b band. Further, with the increase in the number of Bluetooth bad channels the throughput decreases faster and even with fewer Piconets. When Bluetooth devices select channels outside 802.11b band then both work in peaceful coexistence. The collocation of the 802.11b devices and the Bluetooth devices is altogether a new field and it needs more

rigorous analysis of the coexistence. AFH fails to combat the interference problem when in collocation. The proposed algorithm shows some improvement in the performance but the performance degrades as more number of Bluetooth Piconets operates in the close vicinity of 802.11b devices.

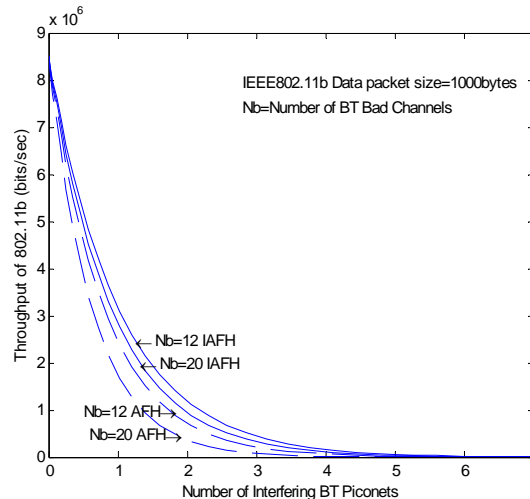


Figure 8: Throughput vs. number of interfering Piconets.

## 5. CONCLUSIONS

In this paper, an Interference-Aware Adaptive Frequency Hopping (IAFH) algorithm is proposed to improve the performance of 802.11b networks in the presence of interfering Bluetooth devices. A more accurate mathematical model is derived for adaptive frequency hopping (AFH) and the proposed IAFH algorithm. From the experiments and numerical analysis, the effected of collocated Bluetooth Piconets on 802.11b networks is significant even when there is one Piconet in the case of the generic frequency hopping. Simulation results indicate that, with the proposed algorithm, the throughput of the 802.11b networks is improved while the probability of collision and the packet error rate are decreased significantly. Hence, it can be concluded that by applying the proposed IAFH algorithm, more number of 802.11b devices and Bluetooth devices can coexist when both of them are operating in close proximity.

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