An Adaptive Frequency Hopping Technique With Application to Bluetooth-WLAN Coexistence

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***Abstract*— In this paper, a new adaptive frequency hopping (AFH) technique is proposed in an attempt to mitigate the interference between Bluetooth (IEEE 802.15) and wireless local area networks (WLANs) (IEEE 802.11b). The new AFH technique optimizes the carrier spacing according to the network load and noise level. For a given overall bandwidth and data rate, reducing the separation between adjacent channels has a positive effect of increasing the number of available hopping channels. This can definitely lead to decreasing the collision rate. On the other hand, decreasing the channel spacing increases the adjacent channel interference. Therefore, there exists an optimal channel spacing that maximizes the network throughput. Rayleigh fading was considered and results show that the new AFH technique outperforms existing AFH techniques for a wide range of network loads.**

I. Introduction

The unlicensed Industrial, Scientific, and Medical (ISM) is a duty-free band, which has the aptitude for a strong growth because of its universal availability and low cost radio suitability. In general, spread spectrum (SS) radio technology provides robustness against various kinds of interference and multipath distortion. In particular, frequency hopping spread spectrum (FHSS) was used in wireless personal area networks (WPANs), such as Bluetooth technology. However, wireless local area networks (WLANs), such as IEEE 802.11b standard, uses a 22-MHz direct sequence spread spectrum (DSSS) to mitigate interference. Although the FHSS radio technology performs well for Bluetooth networks, it may result in a serious problem for nearby WLANs. This is a possible case because the packet transmission durations for WLAN devices are considerably longer than the Bluetooth hopping interval, and thus causing multiple chances for interference collision. On the other hand, the number of interferers in the ISM band has unrestricted access, and hence the increase of their number results in a graceful degradation of the network performance.

In this paper we attempt to tackle the problem of wireless resource management and aim at optimizing the bandwidth efficiency and maximizing the throughput. The main challenge is how to reduce the effect of the interference on the network throughput. The Bluetooth special Interest group (SIG) and the IEEE have have developed the following approaches [3]:

1) Collaborative techniques, where devices avoid one another's activity while easily sharing information (i.e., manual switching, driver layer switching and MAC layer switching).
2) Non-collaborative techniques, where devices must adjust their behavior to avoid interfering with others (i.e. adaptive FH (AFH), adaptive fragmentation, power control, listen-before-talk (LBT) and packet scheduling).

In this paper we propose a new non-collaborative coexistence mechanism for the unlicensed wireless networks.

The concept of AFH was introduced to mitigate interference between Bluetooth (IEEE 802.15) and WLAN (IEEE 802.11b,g). These technologies operate on the same spectrum and will often be in close proximity, thus may interfere with each other. They are also inherently resistant to other wireless devices due to using SS technology. In Bluetooth, FHSS is used where a device transmits an energy burst in a narrow frequency band of 1-MHz before it pseudo-randomly hops to another frequency [3]. In 802.11b, the DSSS is used in which energy is distributed across a 22-MHz channel without hopping [9]. Depending on the signal strength levels, interference occurs when Bluetooth transmission takes place on a frequency within the frequency space occupied by WLAN and packets are transmitted at the same time. Although, 802.11b uses carrier sense multiple access with collision avoidance (CSMA/CA), it is still not able to neither detect nor avoid interference resulting from Bluetooth due to the rapid nature of the FHSS in Bluetooth. However, a Bluetooth device is able to detect interference from WLAN. The Bluetooth SIG and IEEE 802.11b have proposed an AFH in an attempt to allow the coexistence between Bluetooth and WLANs.

AFH [2,5] is an intelligent method to avoid interference via hopping over clear channels only. The basic idea of AFH is to classify channels as either good or bad, and alters the hopping sequence to avoid bad channels. AFH is a non-collaborative technique since there is no information exchange between devices due to the architecture of different wireless technologies. In other words, there is no mutual mechanism to exchange information among different wireless standards.

The paper is organized as follows. Section II provides an overview of existing FHSS techniques. In Section IV, a new AFH is proposed and results are discussed in Section V. Conclusions are discussed in Section VI.

II. Bluetooth FHSS Algorithms

In this section we review existing FHSS algorithms as applied in Bluetooth networks.

A. *Original Bluetooth FHSS*

Bluetooth has been designed to operate in noisy radio frequency environments and apply a fast acknowledgment of packets using FHSS. Interference from other systems operating in the same ISM band is avoided by rapidly hopping to a new frequency each time after transmitting or receiving a packet.

In comparison to other systems operating in the same ISM band, the Bluetooth radio has a fast hopping rate of 1600 hops per second and uses short packets. The use of short packets and fast hopping leads to limiting the impact of other sources of interference. Hopping out and into a continuous range of frequencies that are subject to noise gives the communications link a better chance to remedy transmission errors when out of the distributed frequencies, than would have been the case if the transmission had stayed for several time slots within the noisy frequency range. Therefore, the interference effect is spread over the whole frequency range in a random fashion [3].

B. *Adaptive Frequency Hopping (AFH)*

AFH is a modification of the legacy of Bluetooth FHSS scheme. Two basic algorithms; namely, the reduced channel FH scheme (RC-FHS) and the intelligent FH scheme (IFHS) were combined together to create the existing AFH. AFH works in two modes; namely, Mode-L, which is based on RC-FHS and Mode-H, which is based on IFHS. The operation mode relies on the minimum number of channels, in which a Bluetooth system must hop over.

In Mode-L, the number of good channels is more than the minimum channels to hop over; thus, bad channels are completely avoided. If an original hopping sequence results in a bad channel, this channel is replaced or remapped to a good channel. In Mode-H, the number of good channels is less than the minimum channels to hop over; thus, bad channels cannot be avoided and must be used to satisfy regulations. If a bad channel is used, grouping or pairing must be applied. This means that good channels will be in one partition and bad channels in another partition; but not all channels will be in either partition. These two algorithms that were proposed by IEEE 802.15.2 differ in the way of their adaptively hopping method. Table I shows the classification of AFH algorithms.

AFH promises to reduce the number of retransmissions required by avoiding bad channels, which results in less latency and lower overall interference power in the ISM band [1]. For instance, the earlier Bluetooth specification hops across 79 channels of the available 83.5 channels in the 2.4 GHz frequency band. When AFH is applied, Bluetooth will be able to minimize its hop-sets to 15 channels, leaving up to 68 channels free from hopping sequence.

One challenge of implementing AFH is the legacy device support. This means old Bluetooth devices need to be able to function and communicate with the new specification to support AFH. Nevertheless, AFH promises to modify the legacy of Bluetooth hopping sequence scheme and is currently being developed to be included in the new Bluetooth Specification 1.2 [3]. In order for Bluetooth to allow the implementation of AFH, few modifications must be applied to the current Bluetooth standard. This involves changes to the Baseband, Link Manager Protocol (LMP) and Host Controller Interface (HCI) layers of Bluetooth protocol architecture [2].

While AFH offers many advantages, it still has a few limitations. AFH mitigates fixed frequency interferers, which occupies a fixed spectrum of the ISM band; but it is unable to address dynamic frequency interferes between Bluetooth piconets. In fact, the use of RC-FHS algorithm will lead to less available channel that may result in increasing packet collision among Bluetooth piconets. This means that AFH may increase frequency dynamic interference although it may decrease frequency static interference effect [1]. However, AFH can be considered an effort to allow coexistence of the unlicensed wireless networks. Further research is currently in progress to provide a total solution to allow wireless networks to coexist in harmony.

RC-FHS scheme identifies fixed sources of interference and excludes them from the list of available channels [5]. This scheme needs changes to the existing Bluetooth specification. The first generation of the Bluetooth physical layer specification requires a minimum of 79 frequency channel with a hop rate of 1600 hop per second. But, the Bluetooth Core specification version 1.2 includes AFH as a method for coexistence between Bluetooth and 802.11b. This new specification requires a minimum set of 20 channels only.

Whilst the IFHS scheme designs a new sequence, which aim to maximize throughput or minimize packet loss while still complying FCC regulation by maintaining uniform hop of all 79 channels. In IFHS, the Bluetooth's master complies a list of good and bad channels, and determines block lengths for both good and bad channels as a function of traffic type. In order to ensure synchronization, the master passes this information along with a notification whether devices will be silent during a block of bad channels to its slaves in the corresponding piconet via a reliable broadcast message. Master must specify the starting and ending time for the use of IFHS. If synchronization is lost, all devices will revert back to original hopping sequence and restart IFHS again.

III. A New AFH Algorithm

Wireless technologies such as Bluetooth are subjected to two types of interference. The first type is the persistent interferers caused by DSSS such as 802.11b devices, whereas the second type is the dynamic interferers caused by multiple FHSS devices within close range to each other [4]. A number

TABLE I
CLASSIFICATION OF AFH ALGORITHMS.

Characteristics	RC-FHS	IFHS
Modified Layers	Baseband and LM	Baseband
Coexistence Mechanism	Non-Collaborative	Non-Collaborative
Available Hopping Channels	Less than 79	79
Partition Transmission	No	Yes - Good/Bad
AFH Scheme	Isolate and avoid bad channels	Minimize transmission during bad channels
Implementation Mode	Mode-L	Mode-H

of proposals were introduced above to overcome this problem. To date, current Bluetooth specifications [3] and all other proposed mechanisms to improve Bluetooth frequency hopping assume that channels are orthogonal or non-overlapping because channel spacing is equal to channel bandwidth. AFH mechanism is only ideal for low density of Bluetooth piconets. With less available hopping channels due to AFH and more hopping channels needed to cater the demand for high density of Bluetooth piconets, the probability of packet collision between piconets will increase. Hence, there exist situations where AFH will reduce persistent effect, but increase dynamic interference effect. With overlapping channels, it is possible to tradeoff co-channel interference with adjacent channel interference and as a result to optimize the network throughput.

The concept of channel overlapping is illustrated in Figure 1. Let the non-overlapping channel spacing in existing algorithm of 1 MHz denoted by Δ_0 and the new channel spacing used by the new AFH algorithm be denoted as Δ. The normalized channel spacing,Δ/Δ_0, will always be less than one for channels to overlap ($0 < \Delta/\Delta_0 < 1$). This reduction in channel spacing between channels center frequencies will increase the number of hopping channels that Bluetooth can hop across. The number of channel resulting from overlapped channels is denoted as N_{ch} and can be defined as

$$N_{ch} = \left\lceil \frac{W_{ss} - W}{\Delta} \right\rceil, \tag{1}$$

or inversely proportional to Δ/Δ_0, where (W_{ss} - W) is the available bandwidth. For example, a 22-MHz WLAN will reduce the number of available frequencies to 57 channels with normal AFH. By theory, this new AFH algorithm will double the number of available channels to 114 channels with Δ/Δ_0 = 0.5. For implementation, the new algorithm will be activated only when WLAN is present within proximity such as AFH is implemented. Otherwise, the system remains in normal Bluetooth hopping scheme.

In this new algorithm for a given overall bandwidth and data bit-rate, reducing the separation between adjacent channels has the positive effect of increasing the number of available hopping channels. This can definitely lead to decreasing the collision rate (i.e., reduces the probability of two signals interfering by hopping to the same channel at the same time). On the other hand, the result of decreasing the space between adjacent hopping frequencies will trigger the hopping channels to overlap and the system to become more vulnerable to interference via transmitted signals in the adjacent channels. Hence, it is important to carefully determine the optimum channel spacing value,Δ, such that the adjacent channel interference effect is less than reduction in co-channel interference. This will lead to maximizing system throughput and utilization of radio spectrum [8].

In order to determine the optimum channel spacing, let the total bandwidth of ISM band be represented by W_{ss} and the W is the bandwidth in ISM band occupied by the static interferer. Therefore, (W_{ss} - W) Hz is available for frequency hopping. The proposed AFH algorithm divides available transmission bandwidth, (W_{ss} - W) into N_{ch} channels with carrier frequency f_n, where $n = 0, 1, .., N_{ch} - 1$. Now, assume that signals received at reference filter are applied to raised cosine filters, with the following transfer function

$$H_t\left(f\right) = H_r\left(f\right) \triangleq \sqrt{\lambda\left(f\right)}. \tag{2}$$

where $\lambda\left(f\right)$ in (2) is the square root raised cosine function defined as

$$\lambda\left(f\right) = \begin{cases} 1, & \left|f\right| \leq \frac{1-\beta}{2}, \\ \cos^2\left[\frac{\pi}{4\beta}\left(2\left|f\right| - 1 + \beta\right)\right], & \frac{1-\beta}{2} \leq \left|f\right| \leq \frac{1+\beta}{2}, \\ 0, & \left|f\right| \geq \frac{1+\beta}{2}. \end{cases} \tag{3}$$

Consider a situation where k packets are transmitted during an arbitrary time slot. Let the frequency of i^{th} packet be denoted by f_i where $i = 0, 1, \ldots, (k-1)$. Without any loss of generality, Packet 0 is considered to be the reference packet; meanwhile, other packets act as possible interfering packets. To focus on the effect of overlapping channels, assume that all packets arrive at the reference receiver with equal average power levels. Let the average received power for Packet 0 be $P(0)$, indicating zero frequency offset and the average received power from i^{th} packet is $P(fi - f0)$, indicating frequency offset of $(f_i - f_0)$ where

$$\rho_x = \int |H_r(y)|^2 |H_t(y-x)|^2 dy, \quad (4)$$

where $H_r(f)$ and $H_t(f)$ are the filter transfer functions of the receiver and transmitter, respectively. If an interfering signal is co-channel as the reference signal or completely overlap in time with zero frequency offset, the average power is the maximum autocorrelation value at the center point of the autocorrelation. Otherwise, the average power is zero when frequency offset is more than channel bandwidth.

The special advantage that differentiate this new AFH from the existing one is the increase in the hopping channels, resulting in the reduction of interference at the cost of adjacent channel interference. A packet is considered successfully received if the received signal power exceeds the total interference power by a signal-to-interference (SIR) threshold value, SIR_{TH}, of 10-dB in accordance to Bluetooth specification [3]. This can be calculated as follows

$$P_r(success) = P_r\left(\frac{S}{\sum_{i=1}^{k-1} I_i} \geq SIR_{TH}\right) \quad (5)$$

$$P_r(success) = P_r\left(\frac{\rho(0)}{\sum_{i=1}^{k-1} \rho(f_i - f_0)} \geq SIR_{TH}\right) \quad (6)$$

Upon determining the number of successful packets and total number of packets transmitted, it is possible to determine the throughput, S, which is the average number of successful packets received at the receiver during a time slot.

IV. Numerical Results

Simulation is used to investigate the performance of the new AFH algorithms as a mechanism to avoid interference between Bluetooth and WLAN 802.11b devices. We assume that the Bluetooth devices know the band in which the WLAN 802.11b is operating. Therefore, in order for the new AFH to be implemented in practice, there must be some protocol devised to determine the inaccessible frequencies by Bluetooth piconets. Based on real case scenario used in [6] and [7], there are multiple numbers of piconets in a given area, such that a piconet transmission had the possibility to interrupt the other. At the same time, a WLAN 802.11b 22-MHz DSSS access point (AP) is present. Figure 2 illustrates how multiple piconets act as dynamic interferers while WLAN act as a persistent frequency interferer. In Figure 2, Bluetooth piconet-0 (BT0) acts as the reference piconet and other N piconets act as interfering piconets. The distance between the reference Bluetooth piconet and interfering Bluetooth piconets is fixed at a distance denoted d_1, meanwhile the WLAN AP is at fixed distance d_2. Multipath fading with Rayleigh distribution is assumed throughout the simulations.

The simulation studies the effect of piconet densities, N ranging up to 300 piconets. Although, this may seem to be a large number of piconets, it is critical given the new applications of wireless sensor networks as presented in [9] and [10]. In distributed wireless sensor networks, thousands of sensors are expected to be employed. Therefore, hundreds of piconets are required to operate with minimal interference. To simplify simulation, only one WLAN AP is present and is assumed to occupy the first 22-MHz of the 2.4-GHz ISM band, i.e., channels 1 to 22 from the 79 Bluetooth channels. To determine whether the transmitted packet is corrupted by interference, a SIR calculation at a reference Bluetooth piconet is performed during simulation. If SIR exceeds the threshold value, the packet transmission is not successful and retransmission is necessary. The simulation studies the effect of piconet density with a variable piconet activity probability of $p = 0.2, 0.5$.

A comparison of the proposed AFH with existing FHSS techniques is shown in Figure 4 for an activity probability of $p = 0.2$. We observe that with channel spacing of $\Delta = 0.5$, the performance is slightly better at low density of piconets. However, a channel spacing of 0.75 performs well at a high density of piconets. The same trend is shown in Figure 3 for an activity probability of $p = 0.5$. As discussed above, the new AFH algorithm maximizes the number of available channels to hop across by using the concept of channel overlapping. In Figure 3, we observe that channel spacing of 0.75 and 0.5 provides higher throughput than the original Bluetooth FHSS and the AFH. This is true for all cases except when the number of Bluetooth piconets exceeds 160 piconets, where the channel spacing of 0.5 tends to slightly have less throughput compared to the original FHSS.

V. Conclusion

In this paper a new AFH algorithm was proposed. A comparison was performed between th original Bluetooth FHSS and the AFH schemes. Results show that the new AFH algorithm offers significant throughput improvement compared to the original Bluetooth FHSS and AFH. The proposed AFH algorithm applies the overlapping channel spacing concept that never been considered to date for implementation in Bluetooth. A various number of channel spacing were considered using simulation, among which the most promising channel spacings are 0.5 and 0.75. The new AFH scheme was shown to be more appropriate for low number of Bluetooth piconets.

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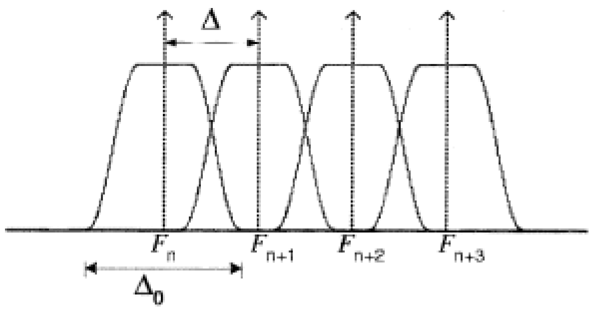

Fig. 1. Overlapped hopping channels.

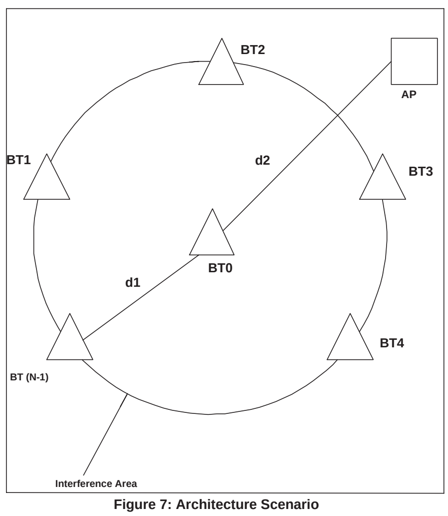

Fig. 2. Interference between Blutooth and WLAN.

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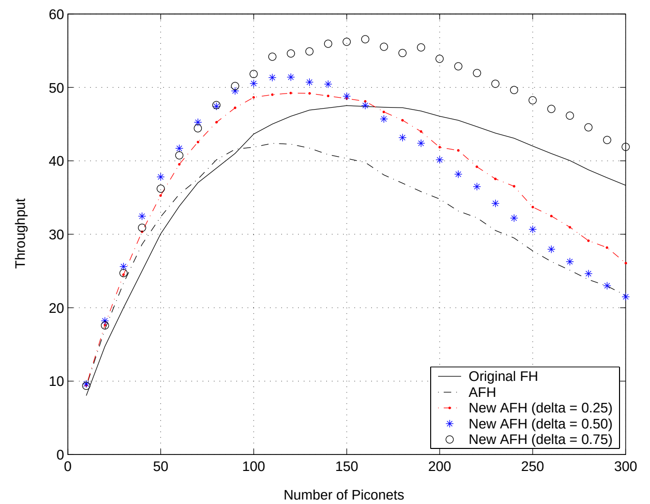

Fig. 3. Comparison of the existing FHSS schemes with the new AFH scheme for an activity probability $p = 0.5$.

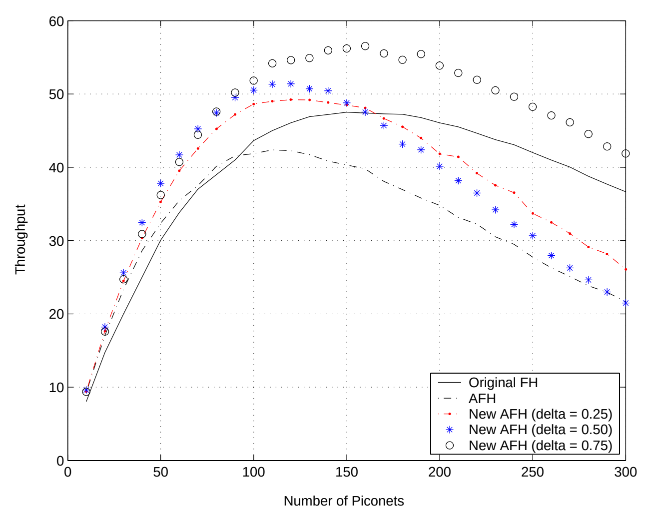

Fig. 4. Comparison of the existing FHSS schemes with the new AFH scheme for an activity probability $p = 0.2$.