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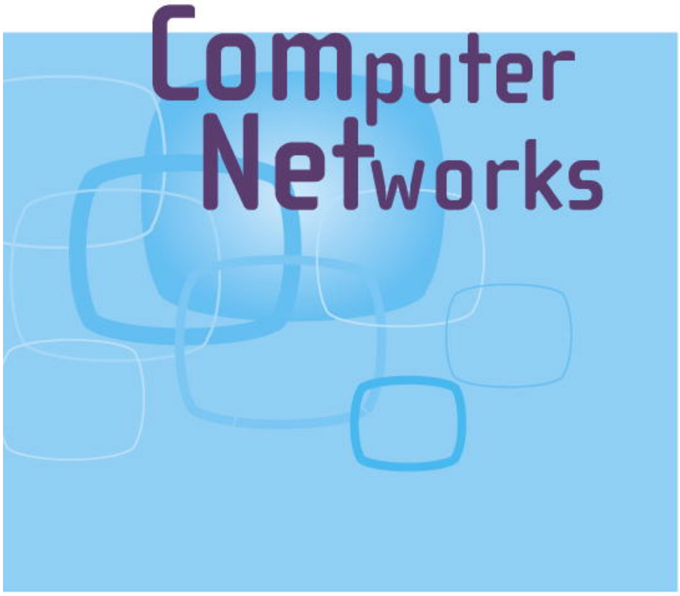

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# Design and evaluation of practical coexistence management schemes for Bluetooth and IEEE 802.11b systems ☆

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## Abstract

Bluetooth and IEEE 802.11b standards share the same unlicensed ISM (Industrial, Scientific, Medical) radio spectrum. As such, severe interference is inevitable and performance can be impaired significantly when heterogeneous devices using the two technologies come into close proximity. We propose a new approach called ISOAFH (Interference Source Oriented Adaptive Frequency Hopping) based on a memory and power efficient channel classification process, thereby reducing the time and space complexity of the mechanism. Through our MATLAB Simulink based simulations of various coexistence mechanisms, we find that the IEEE 802.15 Task Group 2 (TG2) AFH performance is sensitive to memory and power limitations, while ISOAFH is less sensitive to these constraints and can keep a lower channel collision rate. In view of the potential implementation difficulties for AFH based approaches, we also propose a time domain mechanism called ISOMDMS (ISO Master Delay MAC Scheduling).

*Keywords:* Bluetooth; IEEE 802.11b; WLAN; Coexistence; IEEE 802.15; Non-collaborative mechanisms; Adaptive frequency hopping (AFH); Collisions

## 1. Introduction

Bluetooth and IEEE 802.11b are widely used in many short range wireless communication systems. However, as they share the unlicensed ISM radio spectrum, they are susceptible to data transmission collisions when devices with these two different technologies come into close proximity. Fig. 1 shows the conceptual diagram of how interference occurs between Bluetooth and IEEE 802.11b. As can be seen, IEEE 802.11b and Bluetooth share the same

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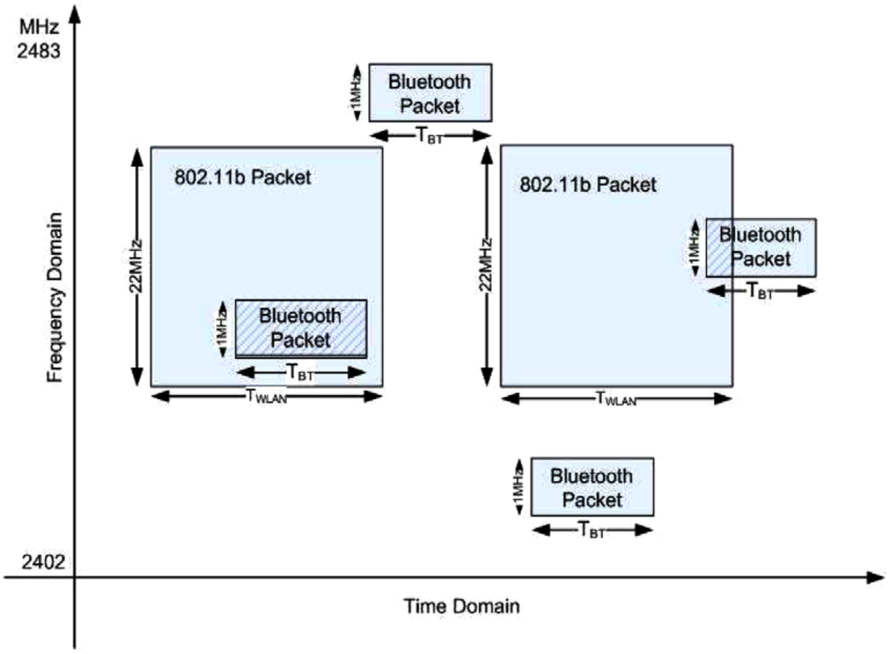

Fig. 1. Transmission collision due to devices coexistence.

2.4 GHz ISM band of 83 MHz in bandwidth. Bluetooth uses FHSS to hop over 79 channels of each 1 MHz in bandwidth [16]. On the other hand, IEEE 802.11b uses DSSS and its carrier remains unchanged and centered on a chosen channel of 22 MHz wide.[1] When IEEE 802.11b is operating, its transmission typically occupies 22 MHz in the spectrum which is the same frequency range shared with 22 of the 79 Bluetooth channels. When a Bluetooth transmission occurs on a frequency that lies within the frequency range occupied by a simultaneous IEEE 802.11b transmission, interference occurs and its severity depends on the devices' separation, signal strengths, etc.

In view of the adverse effects of the coexistence problem [9,12,15,13,23,24,28,32–34], the Bluetooth SIG (Special Interest Group) and IEEE 802.15, have coordinated a task group, known as Coexistence TG2 (Task Group 2) [6,21], to work on this problem.

Coexistence is defined by TG2 as the ability of one system to perform a task in a given (shared) environment where other systems may or may not be using the same set of rules. Usually, those suggested coexistence mechanisms are supposed to be implemented on the Bluetooth side in order to accommodate the existing or intervention of a WLAN system. They work at the MAC (Medium Access Control) layer to make adaptive control, tuning, and coordination, instead of making changes to the existing signal processing methods at the PHY (physical) layer.

Coexistence mechanisms [3,2,4,5,17–19,22,29,39,40] can be classified into two types according to their working principles: collaborative coexistence mechanisms and non-collaborative coexistence mechanisms.

Collaborative mechanisms rely on a communication avenue between IEEE 802.11b and Bluetooth [25,30,31,36]. With the traffic information of each party known beforehand, coexistence is carried out by arranging the transmissions orthogonal in time domain. In fact, such a pre-condition generally requires both system modules to be colocated or within the same physical unit (e.g., within the same PC).

Non-collaborative mechanisms work without any communication between IEEE 802.11b and Bluetooth modules [8]. As such, they achieve coexistence by carrying out two fundamental processes: *channel classification* and *adaptive control actions*. Channel classification is the process for estimating the channel conditions and detecting if there is any interference source nearby. Currently, all non-collaborative mechanisms share some general purpose and common methods for this process, like BER (Bit

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[1] We do not consider the uncommon channel agility option defined in IEEE 802.11b specification.

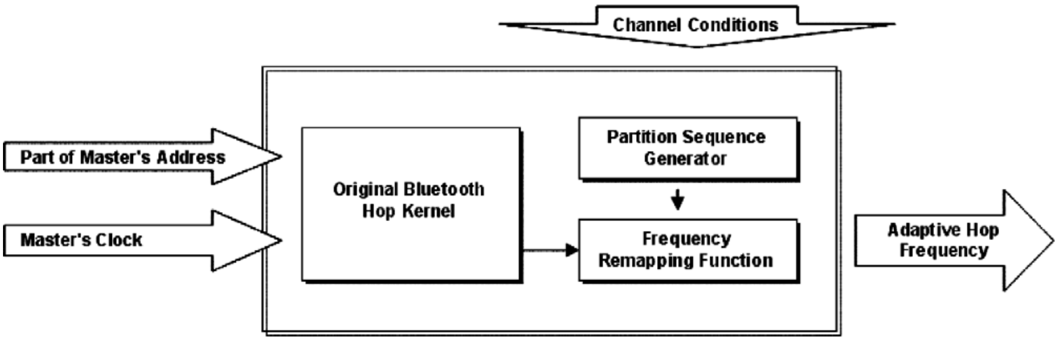

Fig. 2. System architecture of the TG2 AFH.

Error Rate), FER (Frame Error Rate), etc. Based on the results obtained in the channel classification process, the adaptive control actions will take the appropriate collision avoidance actions accordingly. The most notable and important example of non-collaborative mechanisms is the AFH (adaptive frequency hopping) method adopted by TG2 [37,38].

The system architecture of the TG2 AFH mechanism is shown in Fig. 2. The new AFH module is placed between the original hop selection kernel and the frequency synthesizer. The AFH module carries out two functions: sequence generation and remapping. The sequence generation module specifies when and which frequency to use, while the remapping function is used for maintaining the pseudorandom nature within the partition which behaves as the original hop selection kernel.

In TG2 AFH, both the Bluetooth master and slaves take measurement on channel condition, and the usual classification methods are either BER (bit error rate) or PER (packet error rate). The measurements are on a channel-by-channel basis in that slaves send their measured statistics to the master regularly by using LMP messages. The master combines the measurements from all the slave devices and then compiles a list of "good" and "bad" channels. It should be noted that the statistics, recorded in the channel list, are floating point numbers, and hence, require substantial storage.

The master then compares the hopping sequence with the "good" and "bad" channel lists and then determines to bypass or remap it. Afterwards, the master modifies the hopping sequence and then replaces as many "bad" channels as possible by "good" channels. The master informs slaves with the adaptive hopping sequence by using LMP messages.

Although much discussion and performance analysis have been done on TG2 AFH, performance study under practical resources constraint is relatively less explored. Specifically, constraints in memory and power are by and large ignored. For instance, if memory is not enough for storing the complete list of channels, replacement algorithms such as least recently used are needed to refresh the channel table when channel collisions occur. Despite the advancement and miniature of wireless portable devices, power and memory constraints are still always of prime concerns. These concerns are especially true for a FHSS system which is characterized by its simplicity and low implementation cost [10].

In this paper, we propose a new non-collaborative approach called ISOAFH (Interference Source Oriented Adaptive Frequency Hopping) based on a memory and power efficient channel classification process. Our simulation results using Matlab Simulink [7] indicate that the proposed ISOAFH outperforms TG2 AFH in various practical application scenarios. In view of the potential implementation difficulties in AFH based approaches, we also propose a time domain approach called ISOMDMS (Interference Source Oriented Master Delay MAC Scheduling), which works by judiciously deferring transmission whenever a potential collision is detected. We describe our proposed approaches in detail in the next section. In Section 3, we provide a detailed description about the simulation environment and configurations we used in our performance study. Simulation results and their interpretations are included in Section 4. Section 5 provides some concluding remarks.

## 2. Our proposed approaches

In this section, we describe the design of our proposed AFH approach, called Interference Source Oriented AFH (ISOAFH). We then discuss some of the implementation issues, which, in turn, motivate our proposed time domain approach called Interference Source Oriented Master Delay MAC Scheduling (ISOMDMS).

### *2.1. Classification in ISOAFH*

#### *2.1.1. Interference source analysis: IEEE 802.11b*

Our proposed estimation method starts by analyzing the interference source's (i.e., WLAN technologies) transmission characteristics. In particular, we stress on the radio transmission characteristics of IEEE 802.11b. The channel allocation of IEEE 802.11b is shown in Table 1.

By considering the channel assignment, there are 11 channels defined in IEEE 802.11b specification [20]. An IEEE 802.11b system spreads the energy of the transmission signal on the spectrum over a chosen channel of bandwidth 22 MHz. However, the channel allocation is overlapping in nature with each channel separated by 5 MHz. The channels need to be separated by at least five channels to achieve zero overlap. In a small geographical area similar to our envisioned scenarios described in Section 1, the maximum number of non-overlapping channel configuration is CH1, CH6, and CH11 (i.e., 2412, 2437, 2462 MHz). Hence, in such a constrained environment, the maximum allowable connections for IEEE 802.11b is only three; otherwise, the ISM spectrum is considered as overloaded.

#### *2.1.2. Proposed channel estimation method*

According to the above observations, we use the groupings as shown in Table 1 as the foundation of our proposed customized channel classification and adaptive control actions process in the ISOAFH scheme.

Table 1
A comparison of frequency usage by Bluetooth and IEEE 802.11b in the 2.4 GHz ISM band

| IEEE 802.11b channel | Frequency range in use (MHz) | Corresponding Bluetooth channels |
|---|---|---|
| CH1 | 2401–2423 | ch(0–21) |
| CH2 | 2406–2428 | ch(4–26) |
| CH3 | 2411–2433 | ch(9–31) |
| CH4 | 2416–2438 | ch(14–36) |
| CH5 | 2421–2443 | ch(19–41) |
| CH6 | 2426–2448 | ch(24–46) |
| CH7 | 2431–2453 | ch(29–51) |
| CH8 | 2436–2458 | ch(34–56) |
| CH9 | 2441–2463 | ch(39–61) |
| CH10 | 2446–2468 | ch(44–66) |
| CH11 | 2451–2473 | ch(49–71) |

In our proposed channel classification method, we do not intend to find individual "bad" channels. Instead, we try to locate the carrier(s) of IEEE 802.11b interference source(s) and then attempt to avoid hopping on all the affected Bluetooth channels. For instance, according to Table 1, if we can be sure that the carrier of IEEE 802.11b interference is CH3, then we can avoid hopping over Bluetooth ch(9–31) instead of taking measurements for individual channels. Specifically, we group Bluetooth channels into 11 groups according to the channel allocation of IEEE 802.11b, as shown in Table 1. All channels affected by the same IEEE 802.11b carrier are assigned to the same group. It should be noted that this group assignment is overlapping as well in that each Bluetooth channel can belong to more than one group (at most 5 groups). For example, Bluetooth ch10 belongs to Group 1, Group 2, and Group 3. Thus, instead of taking PER for each Bluetooth channel, we only keep track of the PER for that 11 groups only. We use a moving window of 5 Bluetooth time-slots to accumulate the PER statistics. This is formalized in the following rule.

**Algorithm 1.** Channel Classification and Revocation

1. For any channel within group $G_x$ resulted in error, its error rate is used as the aggregate PER (packet error rate) for $G_x$.
2. Furthermore, error in ch($i$) is considered as the error for all groups containing ch($i$).
3. If a group $G_x$ is found to have a PER of $\epsilon$, all channels in group $G_x$ are labeled as "bad" channels.

For example, if a packet sent in Bluetooth channel ch(38) gets corrupted, this packet error is counted in the PER of Groups 5–8. For another example, if Bluetooth channel ch(32) gets interfered, then the packet error is contributed to PER reading of Group 4–7. By doing this, the group corresponding to the carrier of the interference source will have the highest packet error rate value. Thus, the Bluetooth system can locate the carrier of the interference and try to avoid hopping in the whole range of engaged frequencies.

Moreover, compared to the channel-by-channel PER measurement in TG2 AFH, this mechanism can respond faster to interference since the statistics are built up quickly. This is because one error can be counted in more than one group and all errors within a group contribute to a single PER reading.

To implement the measurement of PER, it can utilize the ARQ (Automatic Repeat reQuest) scheme in ACL link. This scheme involves an acknowledgment bit (ARQN) to let the master know whether the last packet was received correctly. The recipient checks each received packet for error, and if error is detected, it indicates this in the header of the return packet. Afterwards, the sender retransmits the packet. Thus, by making use of this scheme, the PER can be measured readily at the sender side.

### 2.2. Adaptive control actions

For TG2 AFH, the master informs the slaves for "bad" channels on a channel-by-channel basis through LMP messages. The slaves then withdraw the "bad" channels from the hopping set. However, this channel-by-channel approach obviously requires more LMP messages and radio resources. Furthermore, it also leads to a longer response time.

In ISOAFH, we define 11 modes of channel revocation, corresponding to the Bluetooth channels affected by IEEE 802.11b channels. When the results of the channel estimation process indicate that any group of channels turns "bad", the master informs its slaves to withdraw the affected channels from the hopping set by using the defined revocation modes. By doing this, the system can reduce the response time to interference but with less LMP messages.

Compared to TG2 AFH, the proposed ISOAFH does not need to maintain the lists of "good" and "bad" channels on a channel-by-channel basis. Thus, a smaller channel table can be used. Moreover, since there are only 11 revocation modes, it is highly feasible to implement them in hardware or firmware to make the process of adaptive hopping sequence generation even faster.

On the other hand, from a practical point of view, we suggest that the maximum number of allowable revocation modes is three since the maximum possible number of concurrent IEEE 802.11b connections is 3 (CH1, CH6, CH11). Thus, the unaffected Bluetooth channels in-between (i.e., ch(21–24) and ch(47–50)) together with those Bluetooth channels are never shared with IEEE 802.11b (i.e., ch(72–78)). In this manner, the FCC regulations and the requirement on $N_{\min}$ can always be fulfilled. In summary, the proposed ISOAFH has the following salient distinctive features:

- exploitation of the potential performance gain by analyzing the interference source;
- faster response compared to TG2 AFH;
- relatively low time and space complexity, leading to less demand on system resources; and
- no need to update the "good" and "bad" channel lists on a channel-by-channel basis.

### 2.3. Implementation difficulties

The information exchange process between the master and its slaves in a Bluetooth piconet is a critical component to make AFH practicable in a real life environment. In our study, in fact we have implicitly assumed that all the Bluetooth devices (i.e., both the master and the slaves) execute the same AFH mechanism, and more importantly, generate the same channel estimation results such that the "good" and "bad" lists are consistent among each other in the piconet. As such, there is no need to "physically" exchange information because the outcomes of the AFH mechanism on each device completely agree with each other. That is, the master does not need to "inform" the slaves to use a different frequency in a future time-slot.

This is in fact a fairly strong assumption because Bluetooth devices are supposed to be of a low cost and thus, it may be infeasible or not cost effective to implement the same AFH mechanism on all Bluetooth devices (be it a master or a slave) in a piconet. For instance, it may be cost effective to implement the AFH mechanism in an access point device but not in a small Bluetooth headset device. If this is the case, then the master needs to inform its slaves about the outcomes of the AFH mechanism, i.e., which new frequencies to use in future time-slots. Then, we face an important implementation issue: how should the master perform such "notification"? This is in fact a rather subtle issue. To see this, consider the single-slot timing diagram in Fig. 3. Suppose the master determines that $f(k+2)$ should not be used but $f'(k+2)$ (where $f'(k+2) \neq f(k+2)$) should be used instead. The subtle issue is that the master has no way to notify the slave because it is about to use $f(k+2)$ to transmit data to the slave. Indeed, the paradox is that the master can only use $f(k+2)$ to notify the slave that $f(k+2)$ cannot be used! In view of this, in fact the master should perform "look-ahead" channel estimation—at slot $k+2$ the master should notify the slave that whether $f(k+4)$ should be used or not (assume that the master can do so by including such

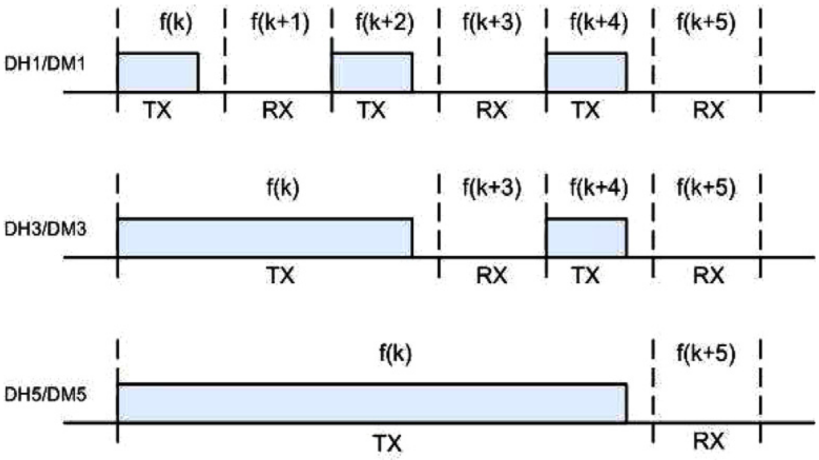

Fig. 3. Slot timing for single and multi-slot packets.

information in a few bits in the packet sent to the slave; this is by itself an implementation research issue of how to encode the new channel number using a few bits). Doing so, however, further aggravates the potential inaccuracy of the channel estimation process because when the channel is used, the estimation result may not be valid any more.

### 2.4. The proposed ISOMDMS

Due to the practical limitations imposed on AFH, we also consider a non-collaborative coexistence mechanism, called Inference Source Oriented Master Delay MAC Scheduling (ISOMDMS), that is easier to implement as it is backward compatible with legacy Bluetooth devices.

For illustration purposes, let us assume that the Bluetooth system is fully loaded (i.e., keep on transmitting) using a single-slot packet type. As can be seen in Fig. 4, the sequence of numbers represent the hopping frequencies to be used for every individual packet in each time slot period. First, based on some channel classification technologies, the device (i.e., the Bluetooth master) obtains the channel conditions and hence, realizes which channels are being engaged by other nearby systems. Second, the master checks against the hopping sequence in pairs (i.e., to protect the Tx and Rx transmission pattern over ACL links) with the channel state information (CSI). Once any of the assigned channels is found to be in the set of "used" (i.e., "bad") channels, no transmission

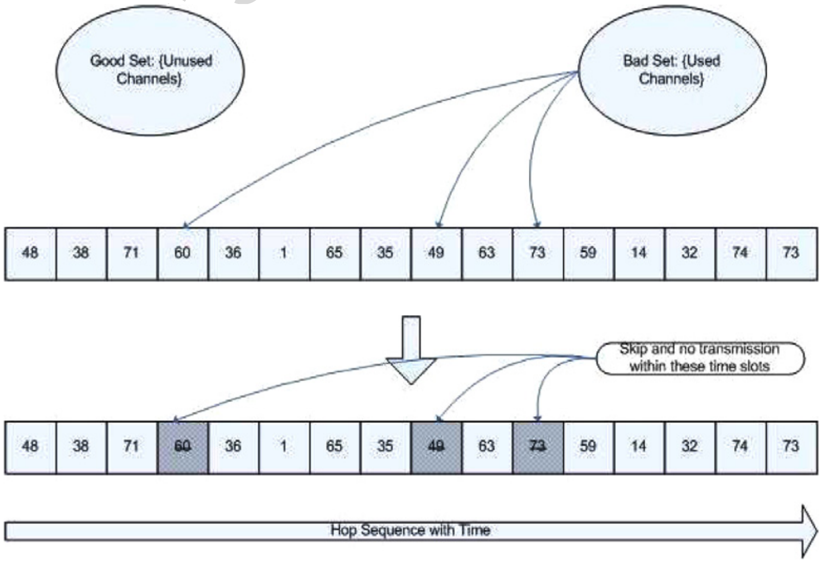

Fig. 4. An illustration of the ISOMDMS mechanism.

is allowed in the corresponding time slot, and more importantly, the affected packet is delayed until the next time slot with a possibly "unused" (i.e., "good") channel.

As described above, ISOMDMS does not impose any change to the original pseudorandom hopping sequence like AFH. However, it can still fulfill the coexistence goals by deferring the transmission if the assigned frequencies are sensed to be occupied. In this manner, Bluetooth devices schedule its traffic in a non-collaborative manner and effectively reduce the offered load during possible collision periods. Thus, compared to AFH, ISOMDMS is a conservative approach in the sense that AFH always aggressively tries to search for a "good" channel while ISOMDMS just tries to stop transmission on interfered channels.

On the other hand, since a Bluetooth master has complete control over the piconet's traffic and the ISOMDMS scheme does not change the original pseudorandom hopping sequence, only the Bluetooth master needs to be ISOMDMS enabled. Yet the whole piconet can enjoy the coexistence performance gain. This meets the requirement on backward compatibility. Furthermore, the adaptive control actions of ISOMDMS are some simple traffic control actions on the time domain and as such, they can be easily implemented by slightly upgrading existing Bluetooth MAC layer firmware. As a result, ISOMDMS is amenable to a low cost implementation.

## 3. Performance evaluation methodology

### 3.1. Simulation configurations

We model a typical application scenario in that various number of devices using Bluetooth and IEEE 802.11b come into close proximity and make connections in an independent manner simultaneously. We used the simulated spread spectrum signal models for Bluetooth and IEEE 802.11b provided in Matlab Simulink toolboxes. The number of piconets and IEEE 802.11b connections, together with the traffic loading of the IEEE 802.11b independent basic service set (IBSS) networks are varied, specifying various levels of system loads. For Bluetooth, each pair of devices independently forms a piconet with ACL links. Masters in the piconets use all the 79 channels defined in the Bluetooth standard to send data to their respective slaves continuously with DH1, DH3 or DH5 encapsulation[2] [1]. On the other hand, we have also included one to three pairs of nodes which form IEEE 802.11b IBSS connections as interference sources. These connections use only non-overlapping channels CH1, CH6, and CH11 as defined in the IEEE 802.11b specification [20].

Table 2
Key simulation parameters

| Parameter | Setting |
|---|---|
| IEEE 802.11b traffic loading step size | 9% |
| Simulation time per step | 10 s |
| Diameter of coverage | 2 m |
| Path loss and channel model | AWGN |
| Bluetooth system loading | 100% |
| Bluetooth packet types | DH1, DH3, DH5 |
| Bluetooth transmitted power | 1 mW (0 dBm) |
| $\epsilon$ (PER threshold) | 2 per moving window of 5 time-slots |
| IEEE 802.11b system loading | Variable (Poisson distribution) |
| IEEE 802.11b data rate | 11 Mbps |
| IEEE 802.11b transmitted power | 25 mW (14 dBm) |

In a multiple-piconet environment, each piconet is assigned a fixed master address throughout all the simulations. Moreover, in our model, the transmissions of different piconets are also governed by an arbitrary phase delay referenced to a designated piconet, say, piconet 1. Thus, measurements are made at the designated piconet 1. A collision event is counted whenever there is clash in the frequency domain with respect to piconet 1's channels (counted once in case of multiple interference sources).

There are some other particular modeling requirements for individual cases and they are described in subsequent sections. Other general simulation parameters are listed in Table 2.

Furthermore, based on the parameters listed in Table 2, the *interference range* [27] (i.e., the maximum distance at which two heterogeneous devices interfere with each other, when they use the same frequency for transmission), denoted by $r_{\text{int}}$, we used in our simulation models is computed as:

$$r_{\text{int}} = d\left(S_{\min}\frac{P_{\text{BT}}}{P_{\text{IEEE}}}\right)^{\frac{\alpha}{2}} \tag{1}$$

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[2] Due to space limitations, not all results are shown in this paper but can be found in [2].

where $S_{\min}$ is the minimum acceptable signal-to-noise ratio needed for proper operation of each mobile device (we used 10 dB in all of our simulation trials), $d$ is the physical distance between any pair of heterogeneous devices (we varied $d$ in the range of 10–20 m), $\alpha$ is the path loss exponent (we used $\alpha = 4$ in all our simulation trials), $P_{\mathrm{BT}}$ and $P_{\mathrm{IEEE}}$ are the transmitted power by a Bluetooth device and an IEEE 802.11b device, respectively (as indicated in Table 2). For a detailed derivation and discussion on the interference range and received signal-to-noise ratio, the reader is referred to Chapter 13 (pp. 520–530) of the book [27].

### 3.2. Performance metrics

Instead of using traditional throughput and/or goodput analysis which is in fact quite superficial, we try to quantify the performance of various AFH mechanisms more accurately by using two metrics: overall channel collision rate in frequency domain, and frequency spectrum usage. The rationales for our performance analysis with these two metrics are as follows:

- Channel collision occurs when two or more systems contend for the same frequency at the same time. The overall channel collision rate is the ratio of the total number of collisions occurred in all channels divided by the total number of frequency hops during the life time of the connection. Conventional throughput analysis is an aggregate measurement of the overall system performance. As such, it is affected by various parameters in all layers. Thus, in particular, it is not a precise performance index for AFH mechanisms. By contrast, the collision rate demonstrates how well or how badly an AFH mechanism works to avoid interference, and it can assess AFH solely by excluding all other effects.
- A frequency spectrum usage diagram shows the number of times a channel used versus the respective channel number. In our study, the channel is numbered according to the Bluetooth standard since we are attempting to study AFH of Bluetooth systems. The spectrum usage diagram depicts the utilization of the available channels in the ISM spectrum. Indeed, a frequency spectrum usage diagram not only gives us a direct visual sense about the total spectrum usage but also reveals much insight about the utilization of the precious bandwidth resources. Moreover, it gives us clues about whether a higher overall network capacity or lower interference level is indeed achievable.

### 3.3. Simulation scenarios

Two types of scenario are set up to compare the performance of all the three mentioned mechanisms, namely pseudorandom FH, TG2 AFH, and ISO-AFH, using three different transmission modes (i.e., DH1, DH3, DH5).

Like many related studies [3,11,14], we have made the following assumptions in all the simulations: mutual interference, that can possibly change the traffic distribution for individual system, is ignored in order to make the analysis manageable. Furthermore, we assume the negotiation and information exchange (e.g., for agreeing upon a new frequency to use) between the master and slaves are done reliably. We discuss more about this issue below.

#### 3.3.1. Modeling of resource limited scenarios

The goals of these simulations are to analyze different AFH mechanisms quantitatively with memory and power constraints. We vary the system load of the IBSS (IEEE 802.11b connections) to see its effect on the Bluetooth devices.

- *Case 1.1 Memory Limited Environment:* The aim of this scenario is to quantify the performance of TG2 AFH mechanism with limited memory, which is modeled by restricting the buffer size for the AFH to store individual channel's information. A sufficiently high refreshing rate of the channel lists is assumed so as to ensure that no channel collision is ascribed to inappropriate refreshing rate.
- *Case 1.2 Power Limited Environment:* The goal of this testing scenario is to investigate the performance of AFH mechanism with power constraint, which is modeled as a limited refreshing rate since more rapid refreshing expends more power. Ample space of memory is assumed so that all channel collisions are due to refreshing rate issues.

#### 3.3.2. Modeling of congested environments

The objective of this simulation is to find out the performance of AFH mechanisms in a congested environment. Two different scenarios are simulated.

- *Case 2.1 Homogeneous Congested Environment:* This simulation case tests AFH performance in a high density, non-static, and narrowband interference environment. Various number of Bluetooth devices are simulated with each pair of them forming piconets independently. In each piconet, the master keeps on sending data to its slaves. Time reference and measurements are made on a single referenced piconet, as described before. Collision rate is measured against different number of piconets. Multiple sources collide on the same channel simultaneously is counted once only.
- *Case 2.2 Heterogeneous Congested Environment:* This simulation case tests AFH performance in a heterogeneous and spectrum-congested environment. In addition to the piconets simulated in Case 2.1, some extra IEEE 802.11b ad hoc mode connections are simulated. Such an ad hoc IBSS network is modeled as background interference sources with two cases of constant traffic load: 50% and 100%. Again, collision rate with reference to a chosen piconet is measured against number of piconets.

## 4. Simulation results and interpretations

### 4.1. Memory limited environment

Fig. 5 shows the collision rate of TG2 AFH with different limited memory available versus different interference levels. The results show that TG2 AFH mechanism is severely affected by the memory available. We can also see that the collision rate increases rapidly when the number of "bad" channels is larger than the system memory capacity. More importantly, the TG2 AFH behaves similar to the pseudorandom one under such a limiting scenario.

### 4.2. Power limited environment

Fig. 6(a) illustrates the effect of number of "bad" channels to a memory limited TG2 AFH mechanism. It shows that collision rate increases sharply when more and more ISM band channels turn "bad". In other words, TG2 AFH performance is degraded drastically in a congested spectrum or when different systems come into moderately close proximity.

Fig. 6(b) shows the collision rates when the interference level increases at different rates faster than the updating rate of "good" and "bad" channel lists. The curve at the bottom represents the lowest possible collision rate with a proper channel lists updating rate. The figure shows that improper channel lists updating rate can lead to a collision rate of three times higher compared to a proper one. As expected, collision rate critically depends on the changing rate of the channel conditions. In fact, in order to get the latest information, more frequent channel lists updating should be maintained in a rapidly changing environment (i.e., mobility is high). However, this requirement also mandates a higher power expenditure rate on the system.

Fig. 7 shows the collision rates of different Bluetooth transmission modes with a single IEEE 802.11b source under various load levels. The general trend for all the mechanisms is that collision rate increases with IEEE 802.11b loading. While all the mechanisms are modeled with 11 memory units (we assume that each channel status requires one memory unit), ISOAFH demonstrates a relatively stable and superior performance,[3] while TG2 AFH approaches the pseudorandom frequency hopping behavior.

Furthermore, it should be noted that the collision rates are calculated on a per packet basis (i.e., counting how many packets encounter collision), and thus, a lower collision rate of a multi-slot packet should not be interpreted as a better result. Specifically, for a DH3 packet, each collision entails the loss of three time-slots. Thus, for example, a collision rate of 0.15 actually means a time-slot loss rate of 0.45. Consequently, although the multi-slot results demonstrate a trend similar to single-slot transmission mode, the collision rate grows up much faster with the activity level of interference sources. This suggests that a shorter packet should be used in high interference environments. In the subsequent results, we focus on the cases where DH1 packet type is used. For results of multi-slot packet types, the reader is referred to [2].

From the ISM spectrum usage diagrams (not shown here due to space limitations but can be found in [2]), pseudorandom frequency hopping mechanism hops over all the available channels evenly and as such, has no reaction to interference

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[3] From the results on two or more IEEE 802.11b sources described in [2], ISOAFH also significantly outperforms TG2 AFH which in turn performs slightly better than the pseudorandom FH.

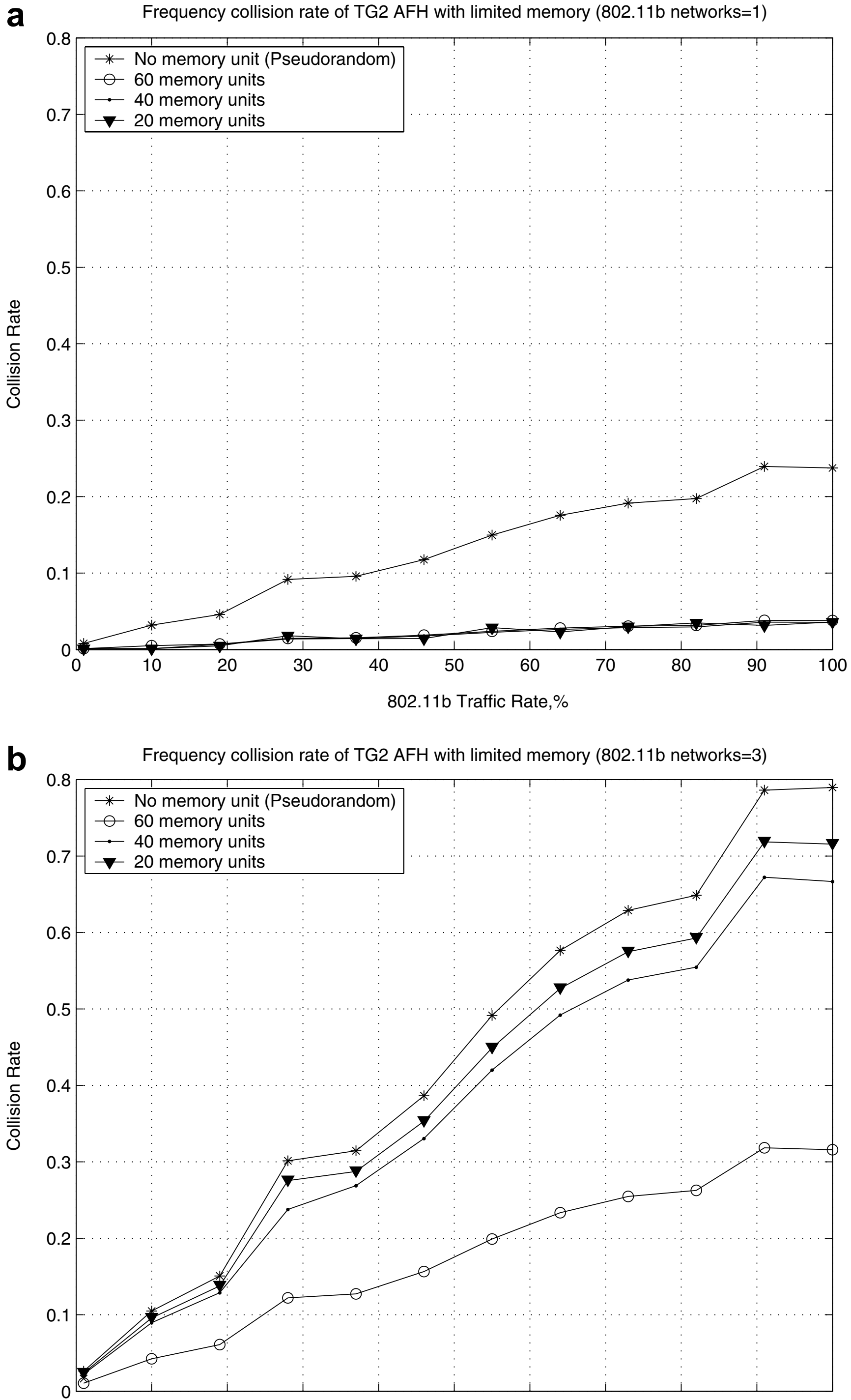

Fig. 5. Collision rate of limited memory TG2 AFH with one to three IEEE 802.11b interference sources. (a) IEEE 802.11b × 1, (b) IEEE 802.11b × 3.

from IEEE 802.11b. On the other hand, both TG2 AFH and ISOAFH can react to the increased collision rate and change the hopping frequency dynamically. Indeed, for smaller Bluetooth packets (i.e., DH1), ISOAFH can achieve a rather stable performance after the IEEE 802.11b load level reaches around 30%. This is because the ISOAFH algorithm continuously avoids using the frequencies occupied by the IEEE 802.11b as soon as such a high load level is reached.

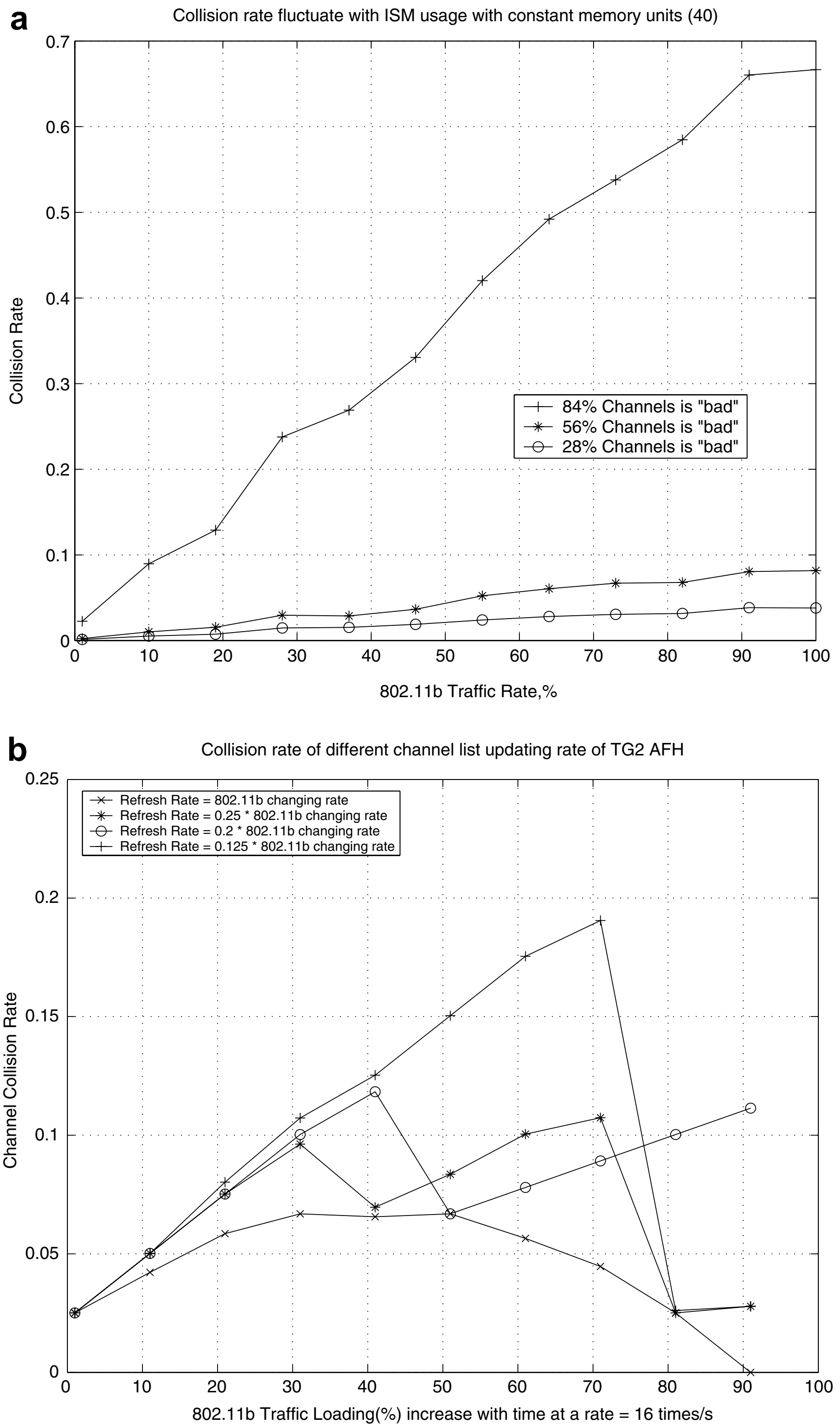

Fig. 6. Collision rate of TG2 AFH under different channel conditions. (a) With varying number of "bad" channels, (b) with varying channel lists updating rate.

### *4.3. Congested environments: homogeneous and heterogeneous cases*

Fig. 8 compares the collision rate of all the frequency hopping mechanisms in the presence of homogeneous and heterogeneous interference sources as an IEEE 802.11b network and varying number of independent Bluetooth networks coexist.

From Fig. 8(a), we can see that the collision rate of all three mechanisms increases with the number

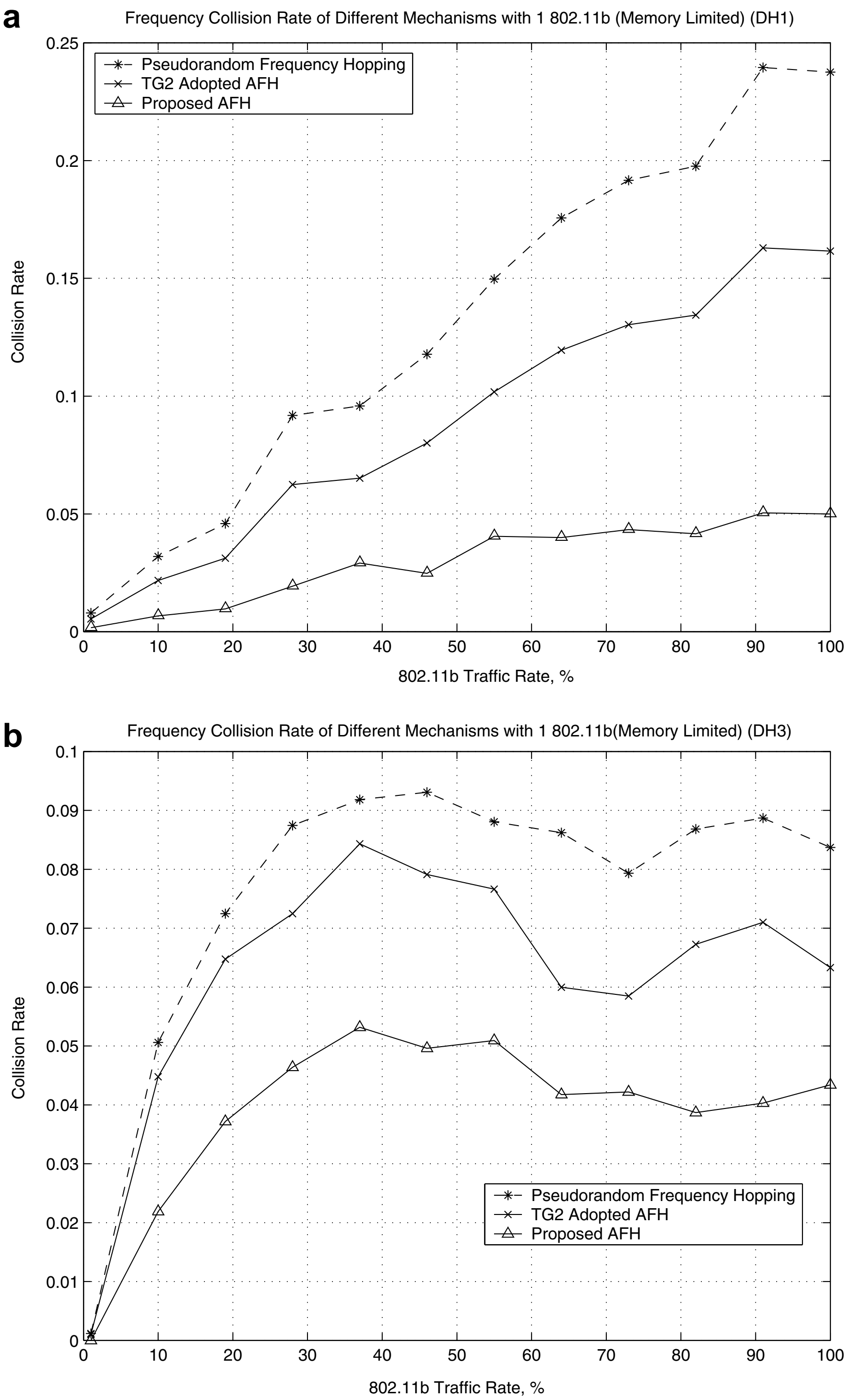

Fig. 7. Collision rate of the three frequency hopping approaches for different Bluetooth packet types in the presence of a single independent IEEE 802.11b interference source with varying load levels. (a) DH1, IEEE 802.11b × 1, (b) DH3, IEEE 802.11b × 1.

of piconets. Furthermore, the three mechanisms show similar collision rates. This is because traffic from the nearby independent piconets confuse the channel classification process in the AFH approaches. Indeed, it is difficult for the channel classification process to accurately identify the interfered channels in the presence of similar narrow band transmissions. However, when a moderately loaded IEEE 802.11b network is present, the interfering nearby Bluetooth piconets cease to be a performance bottleneck, as shown in Fig. 8(b). Specifically, the collision rate of all three approaches

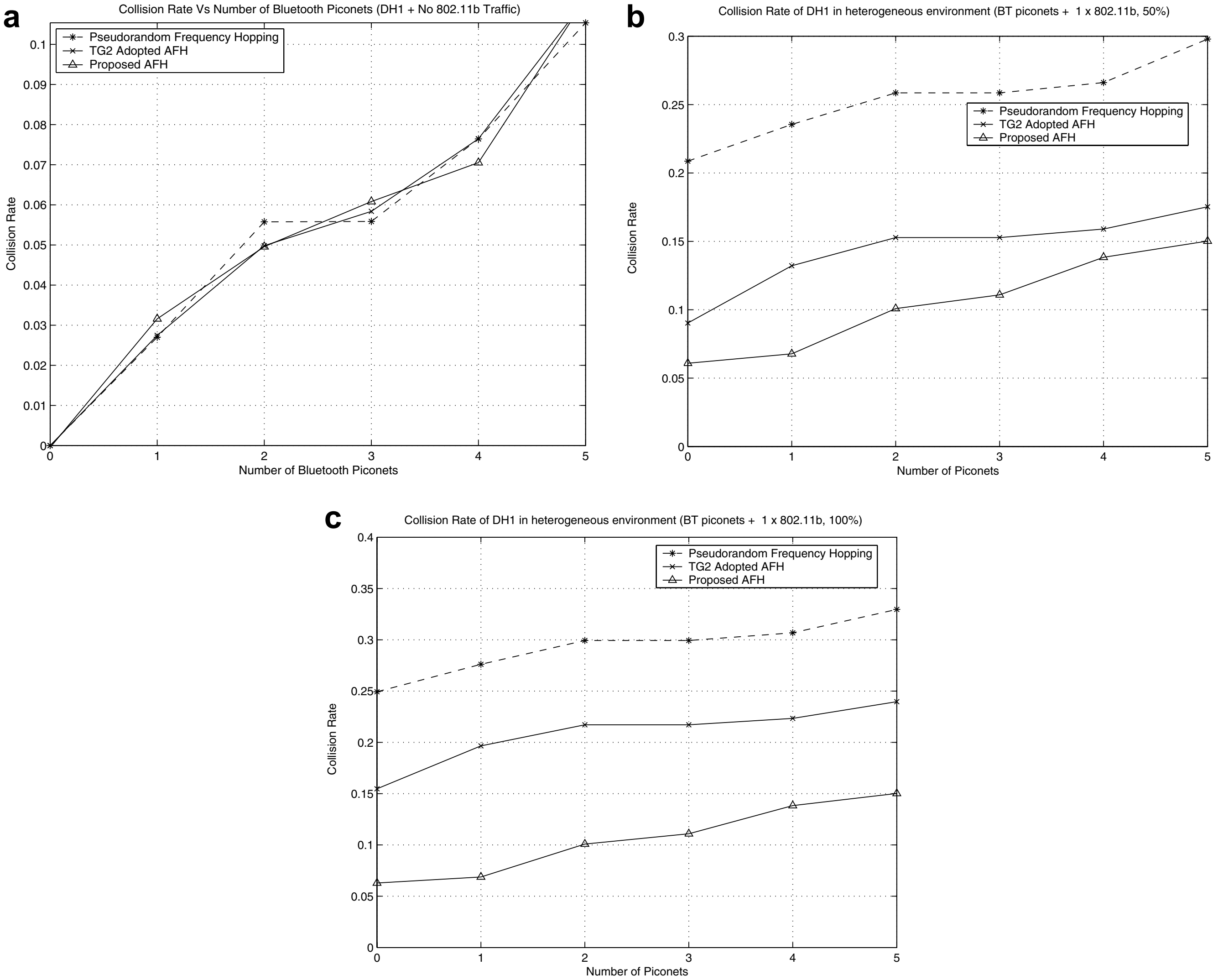

Fig. 8. Collision rate of the three frequency hopping approaches for DH1 Bluetooth packet type in the presence of homogeneous and heterogeneous interference sources—governed by different traffic load levels of an IEEE 802.11b network together with varying number coexisting independent Bluetooth piconets. (a) homogeneous case: no IEEE 802.11b traffic, (b) heterogeneous case: 50% loaded IEEE 802.11b × 1, (c) heterogeneous case: fully loaded IEEE 802.11b × 1.

increase only moderately as the number of piconets is increased. Here, we can see that even though only a single 50% loaded IEEE 802.11b network is operating nearby, the channel classification process in the proposed ISOAFH scheme can pinpoint the correct interfering channels with an accuracy higher than the TG2 AFH. This is because the proposed group-based classification method is tailored for detecting the wide-band IEEE 802.11b transmissions. The performance difference between ISOAFH and TG2 AFH is more profound when the IEEE 802.11b network is fully loaded, as shown in Fig. 8(c).

Finally, we can see that the collision rate in a heterogeneous environment (i.e., Fig. 8(b) and (c)) is larger than the sum of two homogeneous environments (i.e., the IEEE 802.11b only environment in Fig. 7(a) and the Bluetooth piconets only environment in Fig. 8(a)). This is again due to the moderate inaccuracies in channel classification when multiple independent piconets coexist.

### 4.4. Summary of the findings about AFH approaches

We have presented a qualitative and quantitative performance analysis of existing TG2 AFH mechanism and our proposed ISOAFH, which is suitable for low cost mobile devices implementation. Overall, both the TG2 AFH and ISOAFH outperform the original pseudorandom frequency hopping mechanism because extra information about the environment is considered when choosing a hop frequency. For TG2 AFH, "good" and "bad" channel lists and their refresh rate are the core components. The TG2 AFH mechanism can achieve a very low collision rate when there is no resource constraint. However, its performance severely deteriorates when power and/or memory constraints are present. On the other hand, it is encouraging that the proposed ISOAFH approach is found to be insensitive to resource constraints.

Furthermore, our results also show that AFH coexistence mechanisms are inadequate to cope with inter-piconet interference in that the collision rate just keeps on increasing with the number of piconets that are active simultaneously. This is due to the fact that the fast changing and narrowband interference from other piconets largely invalidates the channel classification process of AFH, making the results of channel classification always unable to reflect the current channel conditions.

Another set of simulation results show that compared to the homogeneous scenario (i.e., only IEEE 802.11b or hostile piconets type interference is present, but not both), AFH mechanisms work less efficiently in heterogeneous scenarios (i.e., both hostile piconets and IEEE 802.11b connections are present). This is because, once again, the narrowband interference invalidates the channel classification process and hinders it from identifying the interference from IEEE 802.11b. Though it is an inherent limitation for all AFH, the proposed ISOAFH still exhibits a relatively good performance.

Finally, comparing single-slot and multi-slot transmission modes, we find that multi-slot modes generate a lower collision rate, and hence, smaller loss in time slots when interference level is low (i.e., less than 30–40%). However, the multi-slot collision rate increases much faster than single-slot transmission mode in higher level interference environments, implying a larger loss in data and time slots. This confirms that shorter packets are preferred when channel condition is undesirable and highly fluctuating.

### *4.5. Practical limitations of AFH approaches*

Our study shows that AFH can achieve non-collaborative coexistence effectively when the environment is not too congested and interference source is relatively static in nature compared with the hopping rate of Bluetooth. However, our simulations also reveal the limitations of AFH, in congested environment or when dealing with fast changing interference originated from other Bluetooth piconets. More importantly, such limitations are independent of which AFH mechanism is used. To summarize, we have found that AFH has four inherent limitations:

1. AFH is unable to deal with inter-piconet interference. As shown in the results, AFH is crippled when dealing with fast changing, narrowband interference like Bluetooth itself. Indeed, the collision rate keeps on increasing with the number of Bluetooth piconets nearby. No matter which AFH mechanism is adopted, the performance is the same as that of a pseudorandom FH.
2. AFH is a "best-effort" mechanism. Mobile devices using AFH keep on transmitting whenever there is packet awaiting in the buffer. Though a device always attempts to send on "good" channels, it can still transmit on "bad" channels if the $N_{\min}$ requirement cannot be met. Thus, the performance of AFH might keep on deteriorating when the frequency domain becomes more and more crowded. In our simulations, we find that all AFH mechanisms cannot perform well in a congested spectrum (e.g., two to three WLAN connections nearby). The reason is that they do not get sufficient number of "good" channels to hop with while they still keep on attempting to transmit. Even worse, such an attempt just induces more retransmission traffic for both systems and hence, results in greater potential interference.
3. AFH is backward incompatible because the frequency hopping mechanism is generally implemented in hardware or firmware. As such, implementing AFH generally requires a new Bluetooth chip set design or firmware modifications. Legacy Bluetooth devices cannot benefit from AFH.
4. Performance of AFH is hardware dependent. A high power level of IEEE 802.11b can saturate the Bluetooth receiver and corrupt its packet no matter which channel Bluetooth hops over. This is a typical phenomenon in scenarios where both systems are colocated or separated by less than 1 m [26,35]. In such cases, interference is inevitable even though AFH is applied. Indeed, under such situations, time domain coexistence mechanisms could be better solutions.

### 4.6. Simulation results for ISOMDMS

Fig. 9 shows the throughput of Bluetooth system generated by different types of non-collaborative coexistence mechanisms under different activity level of interference (1–100%) and different congestion levels in the ISM band (with one to three IEEE 802.11b connections) for DH1 packet type.

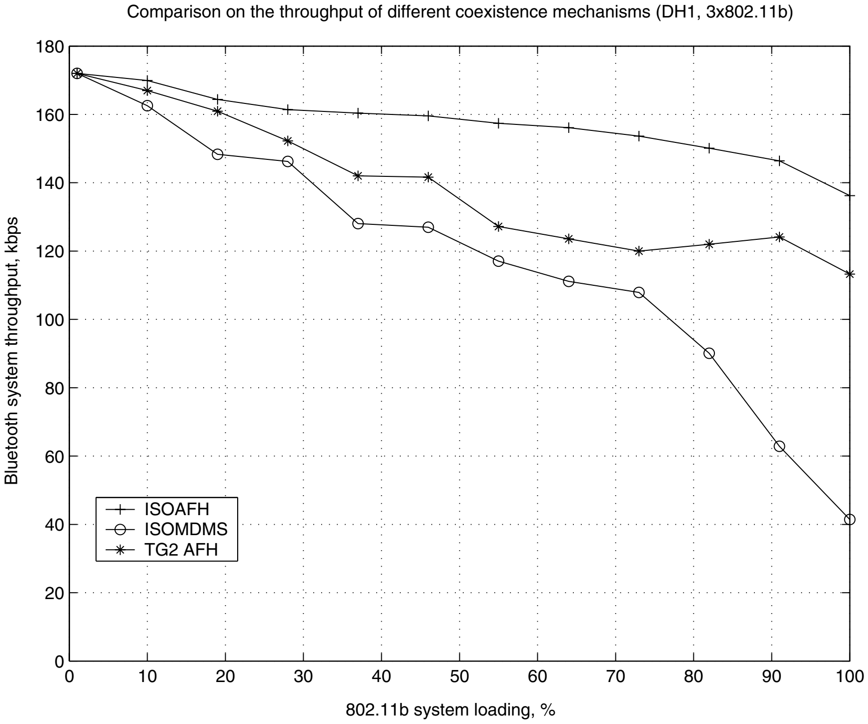

Fig. 9. Comparison of throughput generated by the three different non-collaborative coexistence mechanisms using DH1 Bluetooth packet type in the presence of three independent IEEE 802.11b sources with varying load levels.

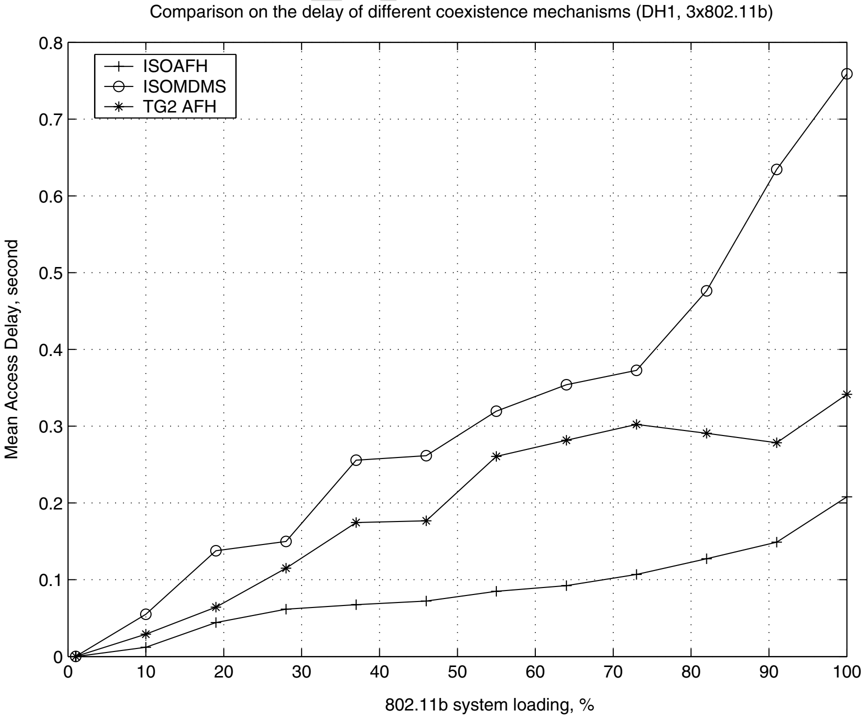

Fig. 10. Comparison of delay generated by the three different non-collaborative coexistence mechanisms using DH1 Bluetooth packet type in the presence of three independent IEEE 802.11b sources with varying load levels.

Fig. 10 shows the corresponding mean access delay results.

Fig. 10 indicates that when IEEE 802.11b interference is low (e.g., <30%), both ISOMDMS and TG2 AFH have more or less the same throughput since the effect of the interference is limited at such a low level of activity, independent of the channel estimation algorithm used. When the interference level increases, ISOMDMS responds in that it realizes the "bad" channels/interference faster, and hence, starts to skip the transmission period with "bad" frequencies assigned. This behavior results in a reduced level of throughput. For TG2 AFH, although it is expected to respond slower than ISOMDMS, the throughput of TG2 AFH is still slightly higher than ISOMDMS since TG2 AFH always hops to a "good" channel.

When the interference level keeps on increasing to a high level (e.g., >60%), both mechanisms can respond to the interference in a shorter time and take the corresponding adaptive actions. However, TG2 AFH always attempts to find a "good" channel while ISOMDMS stops its transmission, and thus, the difference between their throughputs further increases. At very high IEEE 802.11b load levels, the throughput of ISOMDMS drops to a very low level as the interference level becomes very high. This is because as more and more channels are occupied by IEEE 802.11b connections, the ISOMDMS algorithm tends to skip more transmissions. Thus, the throughput drops to an unacceptably low level. In summary, we can conclude that the performance of the time domain coexistence approach is the poorest among all coexistence mechanisms in transmitting single slot packets.

Fig. 10 shows the access delay results. The results are consistent and show that the delayed transmission of ISOMDMS results in the highest access delay for DH1 packets in all interference levels. However, the cost of delayed transmission control starts to pay off in multi-slot transmission modes as long as the interference level is not too high.

Finally, Fig. 11 shows the average packet loss rates generated by the three different approaches with DH1 Bluetooth packets. We can see that ISOMDMS maintains very low packet loss rates for both the Bluetooth and the three IEEE 802.11b networks. ISOAFH's packet loss rates are much higher than those of ISOMDMS because of its inherent risk-taking approach. The performance of the TG2 AFH is the worst. These findings conform to the results reported in [12,13].

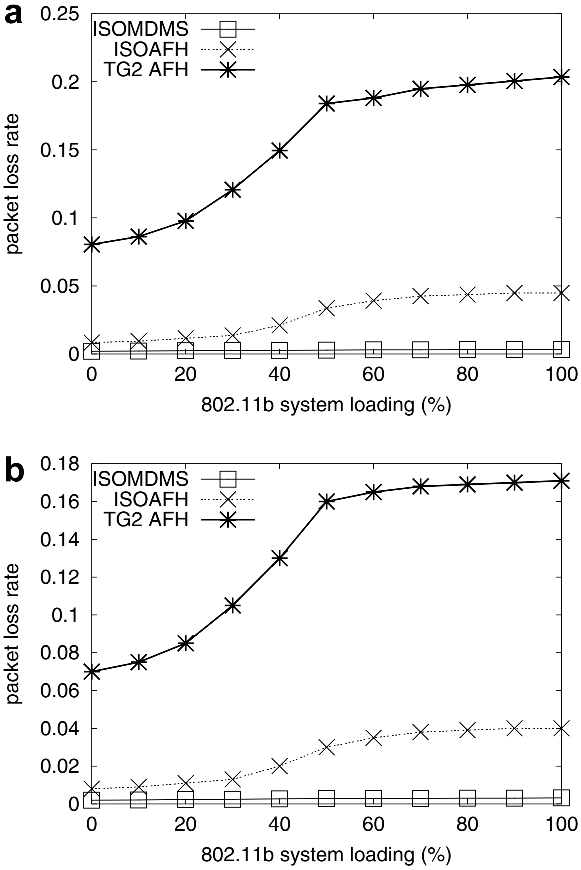

Fig. 11. Comparison of average packet loss rates generated by the three different non-collaborative coexistence mechanisms with DH1 Bluetooth packets in the presence of three independent IEEE 802.11b sources with varying load levels. (a) Bluetooth average packet loss rates, (b) IEEE 802.11b average packet loss rates.

## 5. Conclusions

In this paper, we consider non-collaborative approaches for tackling the coexistence problem involving the Bluetooth and IEEE 802.11b short range wireless technologies. We propose a new AFH (adaptive frequency hopping) scheme called ISOAFH, which is less sensitive to power and memory constraints compared with the existing TG2 AFH method. Furthermore, the proposed ISOAFH can keep a relative low collision rate even in highly congested environments. In view of the practical implementation difficulties in AFH based approaches, we also propose a time domain approach called ISOMDMS, which does not require any change to the original hopping sequence but achieves coexistence by stopping transmission whenever a designated channel becomes "bad". Simulation results based on Matlab Simulink indicate that our proposed approaches are effective in various practical application scenarios.

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## References

[1] Bluetooth Special Interest Group, Specifications of Bluetooth Systems, vol. 1, v.1.0B Core, December 1999.

[2] M.C.-H. Chek, Coexistence Techniques for Heterogeneous Mobile Devices Operating in Uncoordinated Radio Spectrum, M.Phil. Thesis, The University of Hong Kong, December 2003.

[3] C.F. Chiasserini, R.R. Rao, Coexistence Mechanisms for Interference Mitigation between IEEE 802.11 WLANs and Bluetooth, in: Proc. INFOCOMM 2002, 2002, pp. 590–598.

[4] A. Conti, D. Dardari, G. Pasolini, O. Andrisano, Bluetooth and IEEE 802.11b Coexistence: analytical performance evaluation in fading channels, IEEE Journal on Selected Areas in Communications 21 (2) (2003) 259–269.

[5] C. Cordeiro, S. Abhyankar, R. Toshiwal, P. Agrawal, A novel architecture and coexistence method to provide global access to/from Bluetooth WPANs by IEEE 802.11 WLANs, in: Proc. 2003 IEEE International Conference on Performance, Computing, and Communications Conference, 2003, pp. 23–30.

[6] D. Cypher, TG2 Baseline Recommended Practices, IEEE 802.15-01/239r0, 2001.

[7] Developers of MATLAB and Simulink for Technical Computing <http://www.mathworks.com/index.shtml>, 2003.

[8] O. Eliezer, Non-Collaborative Means for Enhancing Coexistence Performance of FHSS Systems, IEEE 802.15-01092/r1.

[9] G. Ennis, Impact of Bluetooth on 802.11 Direct Sequences, IEEE 802.11-98/319, 1998.

[10] M.S. Gast, 802.11 Wireless Networks: The Definitive Guide, Sebastopol, Calif., O'Reilly, 2002.

[11] N. Golmie, N. Chevrollier, Techniques to improve Bluetooth performance in interference environments, in: Proc. Military Communications Conference (MILCOM 2001), vol. 1, 2001, pp. 581–585.

[12] N. Glomie, N. Chevrollier, O. Rebala, Bluetooth and WLAN coexistence: challenges and solutions, IEEE Wireless Communications 10 (6) (2003) 22–29.

[13] N. Glomie, Bluetooth Dynamic Scheduling and Interference Mitigation, ACM/Kluwer MONET, vol. 9(1), February 2004.

[14] N. Golmie, R.E. Van Dyck, A. Soltanian, Interference of Bluetooth and IEEE 802.11: simulation modeling and performance evaluation, in: Proc. 4th ACM International Workshop on Modeling, Analysis and Simulation of Wireless and Mobile Systems, July 2001, pp. 11–18.

[15] N. Golmie, R.E. Van Dyck, A. Soltanian, A. Tonnerre, et al., Interference evaluation of Bluetooth and IEEE 802.11b systems, Wireless Networks 9 (3) (2003) 201–211.

[16] J.C. Haartsen, The Bluetooth Radio System, IEEE Personal Communications 7(1) (2000) 28–36.

[17] J.C. Haartsen, S. Zurbes, Frequency Hop Selection in the Bluetooth Radio System, in: Proc. 7th IEEE International Symposium on Spread Spectrum Techniques and Applications, vol. 1, 2002, pp. 83–87.

[18] I. Howitt, WLAN and WPAN Coexistence in UL Band, IEEE Transactions on Vehicular Technology 50 (4) (2001) 1114–1124.

[19] I. Howitt, Bluetooth Performance in the Presence of 802.11b WLAN, IEEE Transactions on Vehicular Technology 51 (6) (2002) 1640–1651.

[20] IEEE Std. 802.11b, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Higher-Speed Physical Layer Extension in the 2.4 GHz Band, September 1999.

[21] IEEE 802.15.2 Coexistence Mechanisms <http://www.ieee802.org/15/pub/TG2-Coexistence-Mechanisms.html>, 2003.

[22] Y.-K. Kwok, Time-domain, frequency-domain, and network level resource management schemes in Bluetooth networks, in: Mihaela Cardei, Ionut Cardei, Ding-Zhu Du (Eds.), Resource Management in Wireless Networks, Kluwer Academic Publishers, 2004.

[23] J. Lansford, R. Nevo, MEHTA: A Method for Coexistence between Co-Located 802.11b and Bluetooth Systems, IEEE 802.15-00/036r0, November 2000.

[24] J. Lansford, A. Stephens, R. Nevo, Wi-Fi (802.11b) and Bluetooth: enabling coexistence, IEEE Network 15 (5) (2001) 20–27.

[25] J. Liang, Proposal for Collaborative Bluetooth and 802.11b MAC Mechanisms for Enhancing Coexistence, IEEE 802.15-01/080r0, January 2001.

[26] Mobilian: TrueRadio <http://www.mobilian.com/docs/pg/whitepaper.html>, 2003.

[27] K. Pahlavan, P. Krishnamurthy, Principles of Wireless Networks: A Unified Approach, Prentice Hall, 2002.

[28] G. Pasolini, Analytical Investigation on the Coexistence of Bluetooth Piconets, IEEE Communications Letters 8 (3) (2004) 144–146.

[29] J.L. Sevillano, F. Diaz del Rio, G. Jimenez, D. Cascado, A. Civit-Balcells, An analytical model of inter-channel interference in Bluetooth-based systems, in: Proc. 4th Int. Workshop on Mobile and Wireless Communications Network, September 2002, pp. 384–388.

[30] S. Shellhammer, Collaborative Coexistence Mechanism: TDMA of Bluetooth and 802.11, IEEE 802.15-01/025r0, January 2001.

[31] S. Shellhammer, IEEE 802.15.2 Overview, IEEE P802.15-01/313r1, July 2001.

[32] S. Shellhammer, Packet Error Rate of an IEEE 802.11 WLAN in the Presence of Bluetooth, IEEE 802.15-00/133r0, 2000.

[33] M.B. Shoemaker, Proposal for Power Control for Enhanced Coexistence, IEEE 802.15-081/r0.

[34] M.B. Shoemaker, Proposal for Non-collaborative 802.11 MAC Mechanisms for Enhancing Coexistence: Adaptive Fragmentation, IEEE 802.15-01083/r0.

[35] Silicon Wave: Bluetooth + Wi-Fi Coexistence Solutions <http://www.siliconwave.com/coexistence.html>, 2003.
[36] L. Sydanheimo, M. Keskilammi, M. Kivikoski, Performance issues on the wireless 2.4 GHz ISM band in a multisystem environment, IEEE Transactions on Consumer Electronics 48 (3) (2002) 643–658.
[37] B. Treister, H.B. Gan, K.C. Chen, H.K. Chen, A. Batra, O. Eliezer, Adaptive Frequency Hopping: A Non-Collaborative Coexistence Mechanism, IEEE 802.15-01/252r0, May 2001.
[38] B. Treister, K.C. Chen, H.K. Chen, A. Batra, Adaptive Frequency Hopping Clause 14.3, IEEE P802.15-TG2-366r1, July 2001.
[39] B. Zhen, Y. Kim, K. Jang, The analysis of coexistence mechanisms of Bluetooth, in: Proc. 55th Vehicular Technology Conference, vol. 1, May 2002, pp. 419–423.
[40] J. Zyren, Reliability of IEEE 802.11 WLANs in Presence of Bluetooth Radios, IEEE 802.15-99/073r0, 1999.

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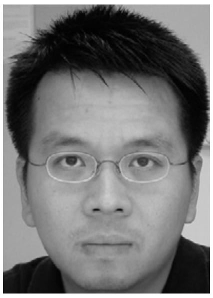

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