Enhanced Adaptive Frequency Hopping for Wireless Personal Area Networks in a Coexistence Environment

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***Abstract*— In this paper, we present an enhanced adaptive frequency hopping (EAFH) mechanism for improving the performance of frequency hopping-based wireless personal area networks (WPANs) under *frequency-static* and *frequency-dynamic* interference. The proposed mechanism monitors the overall packet error rate (PER) of the system to determine the right number of channels to be excluded from the hopset. Then based on the PER of individual channel, it decides whether to exclude a certain channel or not. Finally, proper packet length is associated with those channels remaining in the hopset. These decisions, which pertain to hopset size and packet length, are made so as to optimize the performance of the hopping system in a coexistence environment. We developed an analytical model to justify the behavior and performance of the proposed mechanism. Simulations are conducted under an environment of some collocated Bluetooth (BT) *piconets* and a Wi-Fi network to validate the developed model and show the superiority of EAFH. Simulation results show that, compared with those existing mechanisms including orthogonal hopset-based mechanisms, EAFH could provide much higher throughput while still maintaining reasonably good channel occupancy.**

I. INTRODUCTION

Bluetooth (BT) technology has been adopted in most of the hand-held or mobile devices to replace wired connection of peripherals, and has been a representative technology in Wireless Personal Area Networks (WPANs). To reduce interference between piconets, within a piconet, BT devices communicate with each other via a designated device, called master, using frequency hopping spread spectrum (FHSS) mechanism over 79 channels in the 2.4 GHz unlicensed band (UB). Meanwhile, there are also other types of wireless devices, *e.g.* Wi-Fi or 802.15.4, that operate in the UB. Coexistence between different types of wireless devices that operate in the UB is thus essential. In addition to the noise, there are two other types of interferences, namely frequency-static (FS) and frequency-dynamic (FD) interference, which could cause packet losses. Since a Wi-Fi system rarely changes its operating channels, the interference incidents caused by coexisted Wi-Fi only occur at specific subset of channels, and have high correlation in time. Such kind of interference is thus referred as FS interference. On the other hand, FD interference normally comes from other collocated BT piconets. Because of the FH nature, these interference incidents have little correlation in time or frequency. The FD interference is also referred as self-interference among piconets. The objective of this work is to develop an enhanced frequency hopping mechanism to reduce both FD interference and FS interference, thereby improving the throughput performance of BT piconets as well as other collocated wireless networks.

Besides fragmentation used in [1], hopping set (hopset) manipulation is an alternative approach to reduce the interference. The channels in the hopset are the channels that the device may hop on. Intuitively, we may shrink the hopset by excluding channels that are likely to suffer high FD or FS interference. However, over shrinking the hopset may violate the regulation of FCC [2] on FH and the spirit of UB. For example, if there is a low power UB device, *e.g.* a 802.15.4 device, operates in the proximity of a BT piconet, the low power device is not able to interfere the BT transmission, and thus a BT simply can not notice the coexistence. When the BT piconet shrinks its hopset, it will increase the occupancy of those channels remaining in the hopset. If unfortunately the low power device operates on those channels with increased occupancy, it will suffer more interference. This fact reveals the necessity of *etiquette rules* to bound the hopset shrinkage of a frequency hopping system, such as BT, that has no carrier sensing capability.

The rest of this paper is organized as follows. Related previous work is reviewed in Sec. II. The proposed EAFH mechanism, which could control both packet length and hopset size, is described in Sec. III. The performance of the proposed EAFH mechanism is analyzed in Sec. IV. Computer simulation is conducted and reported in Sec. V to demonstrate the superior performance of the EAFH mechanism. Finally, concluding remarks are drawn in Sec. VI.

II. REVIEW OF PREVIOUS WORK

The problem of coexistence and mutual interference between BT and Wi-Fi has been explored in [3] and [4]. In addition, non-collaborative mechanisms have been developed to enhance the interference mitigation capability of BT. These solutions include adaptive frequency hopping (AFH) [5], [6], Bluetooth interference aware scheduling (BIAS) [7], and data-overlap avoidance (D-OLA) [8]. These mechanisms control the hopset to avoid frequency overlapping with coexisted devices. The basic idea is to distinguish good channels from bad ones (in term of PER) and then let the hopping sequence stay on good channels more frequently than on bad ones.

Because of the unpredictable and ephemeral nature of FD interference, a different approach is taken to solve the problem. The essence of existing solutions is orthogonal hopset adaptation. Theoretically speaking, orthogonal hopsets allows us to eliminate the self-interference completely. However, the advantages are at the price of raising occupancy due to the smaller hopset size. The orthogonal hop set partitioning (OHSP) [9] predefines five hopsets within the original hopset of BT. Each piconet randomly chooses one of the five hopsets without using a procedure for adaptive hopset selection. Due to its small number of orthogonal hopsets, it can serve only small number of collocated piconets that is free from interference. The frequency rolling (FR) scheme [10] adopts adaptive hopset selection and it can thus serve a larger number of collocated piconets. However, it does not inherently posses the ability to deal with FS interference. The dynamic adaptive frequency hopping (DAFH) method [11] can handle both kinds of interference simultaneously. When experiencing high packet loss, it subdivides the current hopset into two subsets of equal size and chooses the one with less interference (*i.e.,* with lower PER) as its new hopset. The partition could be up to 16 subsets with 5 channels in each subset. There is also a procedure to double up the hopset periodically to reverse unnecessary shrinkage. However, the over-shrunk DAFH hopset may result in uneven frequency occupancy (see Fig. 1(b)) and cause unwanted disturbance to other devices.

III. PROPOSED EAFH PROTOCOL

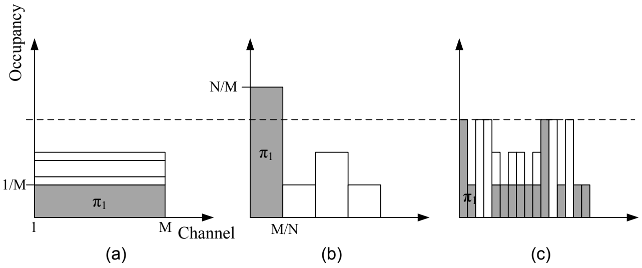
In EAFH, the channels are classified into three groups. Let A be the group of channels using multiple-slot packets, B be the group of channels using single-slot packet, and C be the group of excluded channels. The size of these groups are denoted as $|A|$, $|B|$, and $|C|$, and they add up to the total channel number, denoted as M. The EAFH mechanism is triggered by PER. Each piconet monitors not only the overall PER, denoted as $\overline{PER}$, but also the individual PER of each channel, denoted as $per(m)$ for channel m. $\overline{PER}$ sheds insights on the number of collocated piconets, denoted as N , which will be the upper bound of the number of channels to be excluded from the hopset. The upper bound of the number of channels to be assigned to use multiple-slot packets is also determined in a similar fashion. Besides the upper bound determined by the number of collocated piconets, we also limit the maximum hopset shrinkage not to exceed 50% of the total channels, *i.e.* $\forall i \in N, |C_i| \leq 39$. Within these caps, the decision of EAFH is made on a per channel basis. The details of how does the proposed EAFH mechanism assign channels to different groups to mitigate FD and FS interference is described below.

- Mechanism to mitigate FD interference
  When a piconet recognizes that the interference comes from other collocated piconets, it triggers the adaptation of hopset size and packet length. Among all channels, EAFH assigns N channels to group A ($|A| = N$). At the same time, it deactivates $2N$ channels from hopset to group C ($|C| = 2N$). The rest of the channels remain in group B ($|B| = M - 3N$).
  After initial assignment, EAFH keeps supervising the per of each channel. When a channel in group A has per much higher than $\overline{PER}$, EAFH will swap it with a channel with lower per in group C or B. Swap between group B and C is also possible. This channel swap process can correct the possible misalignment by the initial assignment and periodically updates the member of each group with latest observation.
- Mechanism to mitigate FS interference
  When a piconet senses that some channels constantly suffer severe interference, *i.e.* $per > 0.5$, it will recognize that there is a FS interferer nearby and temporarily remove those channels from its hopset for a longer duration T. Let's denote these channels as group C', a subgroup of C. Channels in this subgroup are also excluded from the regular channel swap process.

Even though we shrink the hopset by less than half of the original hopset size, there may still be serious consequences for other UB devices, especially the low power systems. Etiquette rules are required to alleviate such a problem. While different UB systems have their own specific implementations to serve their own purpose, they, together, must keep the fair sharing of UB regardless of the radio power. In general, it is a challenging job to develop etiquette rules to achieve complete fairness.

Since the original FH mechanism tends to distribute the traffic to each channel evenly, a justifiable etiquette rule for the optimization would be exactly the same. Thus, the average occupancy (or aggregated activity level) of each individual channel with any optimization should be as close to the occupancy of original FH mechanism as possible. In other words, the coexistence mechanism of any adaptive FH algorithms should try to preserve the average occupancy as much as they can.

Fig. 1 illustrates the patterns of occupancy distribution over allocated channels of different mechanisms. In the figure, piconet π_1 is always fully loaded, and thus the activity (traffic load, shown by grey area) G_1 always equals to one. Fig. 1(a) shows the occupancy distribution of piconets under legacy FH mechanism. The activity of all piconets is evenly distributed to each channel. Thus, the occupancy is the same across all channels. The average occupancy of π_1 at any channel is $\frac{G_1}{M} = \frac{1}{M}$. Fig. 1(b) illustrates the occupancy of mechanisms, *e.g.* DAFH [11], that distribute collocated piconets to different orthogonal hopsets. Each shrank hopset is occupied by one piconet exclusively. Since the activity of piconets is different from one another, the occupancy of different orthogonal hopset varies as well. The occupancy of EAFH is shown in Fig. 1(c). Although the occupancy of each channel does not equal to the average occupancy, it is closer to the average than orthogonal hopset mechanisms in general. This is because a piconet in EAFH adjusts its occupancy on any channel according to the interference level. As a result, even when some channels are exclusively occupied by a single piconet, while other channels are shared by several piconets, the occupancy of each channel is still not far away from the average.



(a) (b) (c)

Fig. 1. Illustration of channel occupancy of different mechanisms. (a) Frequency hopping, (b) orthogonal hopset and (c) enhanced adaptive frequency hopping mechanism.

IV. THEORETICAL ANALYSIS

In this section, we developed an analytical model to analyze the throughput and occupancy of our algorithm. Let M be the total channel number and N be the number of piconets. We use π_i to denote the i^{th} piconet, where $i = 1, 2, \cdots, N$, and m to denote the channel index. G_i represents the traffic load (or activity) of piconet π_i. $\tilde{p}_i(m)$ represents the probability that piconet π_i selects channel m. This probability is normalized by packet length.

A. Throughput Analysis

Under EAFH, a piconet distributes more activity to channels with lower utilization, less activity to those already have high utilization, and zero activity to channels experiencing extremely high utilization to uphold the etiquette rules. Thus, the aggregated occupancy of all collocated piconets in each channel is expected to be close to the average with small variation. Since all collocated piconets are expected to have the same size of the three groups, we argue that fraction of piconets in different group in a channel equals to the fraction of channels in different group of a piconet. Let μ be the ratio of $\frac{N}{M}$. On a given channel, we would observe that among the N piconets, $\mu|A|$ piconets assign this channel to group A, $\mu|B|$ piconets assign this channel to group B and the rest of piconets exclude this channel from their hopset. Based on this observation, we start to find various probabilities that will influence the throughput.

For a time slot in channel m, the chance that there is a transmission is denoted as $P_{tr}(m)$, which is the probability that at least one of the N piconets intend to transmit in this channel using a single- or multiple-slot packet.

$$P_{tr}(m) = 1 - \prod_{i=1}^{\mu|A|}(1 - G_i\tilde{p}_i(m)) \prod_{j=1}^{\mu|B|}(1 - G_j\tilde{p}_j(m)) \quad (1)$$

If the time slot is not idle, it could be occupied by one or more piconets using single- or multiple-slot packets. We are interested in $P_{tr}^A(m)$, which is the probability that at least one piconet using multiple-slot packets transmit at the time slot.

$$P_{tr}^A(m) = 1 - \prod_{i=1}^{\mu|A|}(1 - G_i\tilde{p}_i(m)) \quad (2)$$

The successful rate of a transmission using single-slot packet, $P_s^B(m)$, is the chance that only one piconet using single-slot packet transmits at the time slot, while all other piconets are idle.

$$\begin{aligned} P_s^B(m) &= \prod_{i=1}^{\mu|A|}(1 - G_i\tilde{p}_i(m)) \times \sum_{j=1}^{\mu|B|}\{G_j\tilde{p}_j(m) \\ &\quad \prod_{k=1,k\neq j}^{\mu|B|}(1 - G_k\tilde{p}_k(m))\} \end{aligned} \quad (3)$$

Also, the successful rate of transmission using multiple-slot packets, $P_s^A(m)$, is the probability that only one piconet using multiple time slot packet transmits at the time slot, while all other collocated piconets are idle for the whole transmission period, which is 3 time slots in our study.

$$\begin{aligned} P_s^A(m) &= \prod_{i=1}^{\mu|B|}(1 - G_i\tilde{p}_i(m))^3 \times \sum_{j=1}^{\mu|A|}\{G_j\tilde{p}_j(m) \\ &\quad \prod_{k=1,k\neq j}^{\mu|A|}(1 - G_k\tilde{p}_k(m))^3\} \end{aligned} \quad (4)$$

For BT devices, the failed transmission still takes the same amount of time as the successful transmission. Finally, the throughput of channel m is the time fraction that dedicates to the payload during a transmission.

$$\Theta(m) = \frac{P_s^A T_p^A + P_s^B T_p^B}{P_{tr}^A(3T_{slot}) + (P_{tr} - P_{tr}^A)T_{slot}}, \quad (5)$$

where T_p^A and T_p^B are the transmission time of the payload for 3-slot and 1-slot packets respectively. T_{slot} is the duration of a BT time slot.

Eq. 5 expresses the throughput of a certain channel, which is also the overall throughput of collocated piconets, since under EAFH, utilization becomes the same in all channels. For a specific piconet π_i, the throughput θ_i is the inner product $\tilde{\mathbf{p}}_i \cdot \Theta$ where Θ is the vector presentation of the throughput.

B. Occupancy Analysis

The frequency occupancy, denoted as O, describes the maximum aggregated activity level across the allocated frequency, which is proportional to the maximum interference that a device can cause in the worst case scenario.

$$O = \max_{m \in M} \{ \sum_{i=1}^{N} G_i \tilde{p}_i(m) \}. \tag{6}$$

For example, the frequency occupancy of a device using orthogonal hopset mechanism in Fig. 1(b) is $\frac{N}{M}$.

As mentioned before, EAFH tends to evenly distributed the activity to all channels, its occupancy could be expressed as

$$O_{EAFH} \approx \frac{\sum_{i=1}^{N} G_i}{M}. \tag{7}$$

As to the DAFH, the occupancy could be expressed as

$$\begin{aligned} O_{DAFH} &= \max_{i \in N}\{\tfrac{G_i}{M_i}\} &= \frac{2^{\lceil \log_2 N \rceil}(\max_{i \in N}\{G_i\})}{M} \\ & &\approx \frac{N(\max_{i \in N}\{G_i\})}{M}. \end{aligned} \tag{8}$$

By Eq.7 and Eq.8, we show that EAFH has higher occupancy than orthogonal hopset mechanisms, except when all piconets have the same G_i. Regardless of the number of orthogonal subsets, by definition, the frequency occupancy of orthogonal hopset mechanisms equals to the highest occupancy among the subsets which represents the worst interference scenario. On the other hand, EAFH tends to have close to average occupancy on all channels. Thus, EAFH is more coexistence friendly than orthogonal hopset mechanisms.

V. SIMULATION RESULTS

To corroborate the superiority of our proposed EAFH mechanism, simulations under FD and FS interference environment are conducted. The setup of our simulation is to allocate a certain number of piconets at a hotspot (*e.g.* airport lounge, conference room, *etc.*) with or without an FS interferer. Within this hopset setup, interference is always mutually destructive.

For each simulation, we first assigned the number of piconets, then their activity levels are randomly chosen from a uniform distribution in the interval of $[0.0, 1.0]$. Then, the simulation runs one time slot per time until it reaches 1,000,000[slots] or around 10 minutes for a single trial and each plotted value is the average of 30 trials.

For the single-slot and multiple-slot transmissions, we use DH1 and DH3 packets respectively. The detail structure of these Asynchronous Connection-Less (ACL) link packets could be found in the IEEE 802.15 standard [12]. We define the throughput as the time fraction that dedicates to meaningful payload during a transmission. The channel occupancy is defined as the maximum total activity among allocated channels. We first picked the utilization level that is maximal among all channels periodically. Then, the channel occupancy is calculated as an average of these maximal values obtained throughout the simulation.

To put things in perspective, in addition to EAFH, we also simulated several other existing mechanisms. The curve of simple FH mechanism is given to serve as a basis for performance comparison. Adaptive FH mechanism is simulated under FS interference environment to show its capability of offsetting the Wi-Fi interference. We also simulated an orthogonal hopset (OH) mechanism. In this OH mechanism, the allocated channels are partitioned into at most 5 orthogonal subsets. While the number of collocated piconets is not greater than the upper bound, except the overhead for piconets to switch to the unoccupied subset, piconets using OH mechanism are free from FD interference within their orthogonal subsets. However, once the number of collocated piconets exceeds the upper bound, more than one piconet may be found in an orthogonal subset. Then, those subsets with multiple piconets are no longer free from the FD interference.

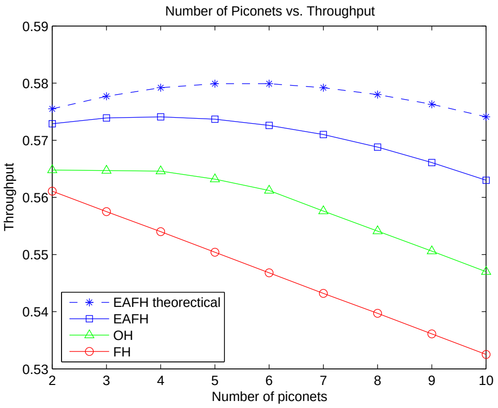


Fig. 2. Illustration of throughput vs. number of piconets under frequency dynamic interference.

Fig. 2 shows the throughput versus the number of collocated piconets under the environment with only FD interference. The performance of original FH mechanism is severely degraded as the number of collocated piconets increases. The orthogonal hopset mechanism has better performance than FH. The degradation was postponed until the number of piconets reaches 5, which is the number of orthogonal subsets. The hopset adaptation to create partially orthogonal hopset along with the adoption of efficient multiple-slot packets transmission gives EAFH the edge over other mechanisms. The theoretical curve reveals the superior performance of EAFH. The performance gain of EAFH is the result of using efficient multi-slot packets on channels with small FD interference. The gap between theoretical and simulated results is due to the overhead of continual channel swaps before reaching the optimal alignment among piconets.

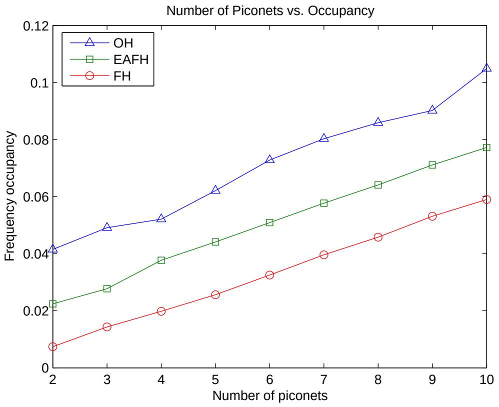


Fig. 3. Illustration of frequency occupancy vs. number of piconets under frequency dynamic interference.

Fig. 3 shows the relation between frequency occupancy and the number of collocated piconets. Under the environment with only FD interference, three mechanisms, namely EAFH, FH, and OH, are simulated. FH has the best occupancy performance because it uses all the available channels. EAFH is designed to improve throughput while following the etiquette rules by keeping the occupancy as low as possible. The increased occupancy is caused by the scenario that multiple piconets accidently choose to transmit multiple-slot packets in the same channel. Channel swap process is responsible to correct such occurrence. However, there is still chance that it could happen, especially in the early stage of adaptation. Orthogonal hopset mechanism does not try to average the traffic across different orthogonal subsets and may result in locally concentrated occupancy. Therefore, it generally has the worst occupancy performance. From the coexistence point of view, OH mechanism is more likely to cause starvation of low power systems in the unlicensed band.

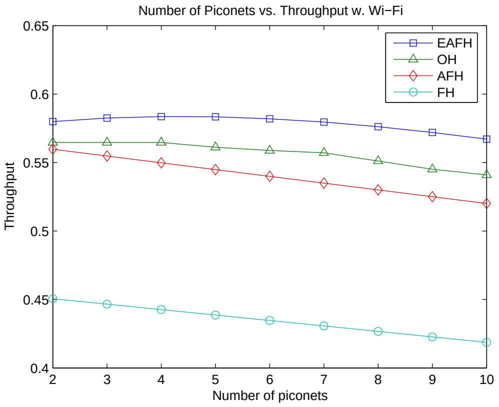


Fig. 4. Illustration of throughput vs. number of piconets under frequency dynamic and frequency static interference ($\tau_{Wi-Fi} = 0.7$ in all 22 channels).

Fig. 4 shows the throughput under both FD and FS interference environment. For FS interference, a Wi-Fi network which occupies exactly 22 channels is used to generate FS interference. The activity level, τ, of the Wi-Fi network is set to 0.7. By adaptive channel turn-off technique, AFH significantly improves the performance over simple FH mechanism. The orthogonal hopset mechanism inherits the channel turn-off technique and also improves the FD interference among remaining channels through orthogonal hopset partitioning. Thus, it outperforms AFH even when only 4 orthogonal subsets remain, since one of them is occupied by collocated Wi-Fi. EAFH also adopts the powerful channel turn-off technique and further improves the coexistence ability of BT devices.

VI. CONCLUSION

An enhanced dynamic frequency hopping (EAFH) mechanism was proposed in this work. EAFH could manipulate hopset size and packet length simultaneously to enhance the coexistence ability of BT devices. An analytical model was developed to predict its performance. The model also revealed the potential of EAFH, which is to increase throughput (or decrease PER) while still maintaining fair occupancy across the allocated frequency channels. Computer simulation was conducted to demonstrate the superior performance of EAFH under frequency-dynamic (FD) and frequency-static (FS) interference.

REFERENCES

[1] A. C.-C. Hsu, D. S. L. Wei, and C.-C. J. Kuo, “Coexistence mechanism using dynamic fragmentation for interference mitigation between wi-fi and bluetooth,” in *MILCOM’06*, Washington D.C., October 2006.

[2] *FCC Part 15.247: Operation within the Bands 902-928 MHz, 2400-2483.5 MHz, and 5725-5850 MHz, in Part15: Radio Frequency Devices*, Federal Communication Commision (FCC) Std. Part 15.247, 2002.

[3] I. Howitt, “Bluetooth performance in the presence of 802.11b WLAN,” in *IEEE Transactions on Vehicular Technology*, vol. 51, no. 6, November 2002, pp. 1640–1651.

[4] N. Golmie, N. Chevrollier, and O. Rebala, “Bluetooth and WLAN coexistence: challenges and solutions,” *IEEE Wireless Communications Magazine*, Dec 2003.

[5] IEEE 802.15 WPAN task group 2 (TG2). [Online]. Available: http://www.ieee802.org/15/pub/TG2-Coexistence-Mechanisms.html

[6] N. Golmie, N. Chevrollier, and O. Rebala, “Bluetooth adaptive frequency hopping and scheduling,” in *Proc. of IEEE Military Communications Conference (MILCOM ’03)*, vol. 5, October 2003, pp. 1138–1142.

[7] N. Golmie, “Bluetooth dynamic scheduling and interference mitigation,” *ACM Mobile Networks*, vol. 9, no. 1, Feb 2004.

[8] C. Chiasserini, R. Rao, and D. di Elettronica, “Coexistence mechanisms for interference mitigation between IEEE 802.11 WLANs and Bluetooth,” *INFOCOM 2002. Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, vol. 2, 2002.

[9] Z. Jiang, V. Leung, and V. Wong, “Reducing collisions between Bluetooth piconets by orthogonal hop set partitioning,” in *Proc. IEEE Radio and Wireless Conf. (RAWCON ’03)*, August 2003.

[10] P. Popovski, H. Yomo, S. Aprili, and R. Prasad, “Frequecny rolling: a cooperative frequency hopping for mutual inteferring WPANs,” in *Proc. ACM Mobihoc Conf.*, May 2004, pp. 199–209.

[11] P. Popovski, H. Yomo, and R. Prasad, “Dynamic adaptive frequency hopping for mutually interfering wireless personal area networks,” *IEEE Transactions on Mobile Computing*, vol. 5, no. 8, pp. 991–1003, August 2006.

[12] *Wireless medium access control (MAC) and physical layer (PHY) specifications for wireless personal area networks (WPANs)*, IEEE Std. 802.15.1, 2002.