Parallel and Gaussian Frequency Hopping for Dynamic Coexistence in the Unlicensed Band†

M. M. Hasan*, Ravi Prakash, and Jason P. Jue

Dept. of Computer Science, The University of Texas at Dallas, TX 75080

SUMMARY

With the surge of short-range wireless applications, more networks are being deployed in the unlicensed radio band. The challenge that emerges is to accommodate these networks without breaching current rules and regulations on frequency usage. This paper studies the coexistence of several independent and dynamic wireless networks using the frequency hopping technique. We propose a novel hopping scheme that minimizes mutual interference and allows more networks to collocate effectively, but does not violate restrictions imposed by the Federal Communications Commission (FCC) regarding frequency constraint (related to the minimum number of frequencies in a hopping set) and time constraint (related to the maximum duration of using a particular frequency). The coexisting networks follow the Gaussian distribution in choosing transmission frequencies from parallel hopping spaces without the overhead of extra message exchange among networks. Simulation results on key metrics such as channel collision rate, goodput, and fairness in channel usage are presented to establish the viability of the proposed scheme in comparison with other contemporary approaches. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: FCC regulations; Frequency hopping; Coexistence; Mutual interference

1. INTRODUCTION

Frequency hopping (FH) spread spectrum is a technique to enable sharing of the unlicensed spectrum among coexisting wireless networks [1]. In FH mode, radio transmission occurs on a pseudo-random sequence of frequencies that is known to both the transmitting and receiving devices. By switching the carrier frequency rapidly, an FH device can avoid others occupying the same band and becomes less prone to be victimized by interference comparing to a device that implements direct sequence spread spectrum (DSSS) [2]. Consequently, FH is widely used in limited range wireless networks, e.g., Bluetooth piconet (IEEE 802.15.1) [3] and one of the physical layers of the IEEE 802.11 specifications [4].

*Correspondence to: 2700 Waterview Pkwy, Apt 4932, Richardson, TX 75080, Email: hasanmm@utdallas.edu
†This work has been supported in part by the National Science Foundation (NSF) under grant no. CNS-0435105. A preliminary and partial presentation of this study has appeared in the proceedings of IEEE International Conference on Communications (ICC), Dresden, Germany, June 2009.

Contract/grant sponsor: Publishing Arts Research Council; contract/grant number: 98–1846389

Copyright © 2000 John Wiley & Sons, Ltd.
1.1. Concerning Issues and Literature Survey

Due to the proliferation of wireless electronics, it is becoming more common to collocate multiple FH based and non-FH based networks. Recent works have shown that the coexistence of multiple such networks may cause severe interference to each other resulting in acute performance degradation [5–10]. Besides, an FH interferer on a DSSS victim is more harsh [2]. Solutions to such problems are sought through software implementations, rather than any electronic hardware adjustments [11]. Researchers have developed an adaptive frequency hopping (AFH) technique for FH systems which scans for “good” channels that are less likely to interfere with other coexisting systems and which jumps among those “good” channels to transmit packets [3, 12–14]. It is observed in [15, 16] that AFH can successfully address the problems of noise (which is not correlated in time and uniformly distributed over the whole set of frequencies) and frequency-static interference (which occurs at channels for a period longer than the packet duration), but cannot handle frequency-dynamic mutual interference (which occurs at channels for a period close to the packet duration). To avoid mutual interference, the authors in [15] propose the orthogonal division of channels into 5 consecutive groups (each group is called a hopset). This approach can support a limited number of collocated wireless personal area networks (WPANs). On the other hand, the authors in [16] propose cooperative rolling of hopsets. This approach can accommodate more WPANs. However, both approaches in [15, 16] cannot inherently deal with frequency-static interference. Therefore, a new technique termed dynamic adaptive frequency hopping (DAFH) is developed that can simultaneously adapt to frequency-static interference and mutual interference [17, 18]. In [19], the authors show that DAFH may cause uneven frequency occupancy across channels due to over-shrunken hopsets. They suggest an enhanced scheme to control the shrinkage of hopsets provided that the total number of collocated piconets is known a priori. The approach in [20] uses dual channel transmission to reduce the probability of packet loss at the expense of an additional channel per transmission and reduced transmission range. In [21], an analytical model to evaluate mutual interference is developed and compared to the empirical test results.

The mutual coexistence schemes discussed thus far do not consider simultaneously the two constraints imposed by the Federal Communications Commission (FCC) on the minimum size of a hopset and the maximum duration of channel occupancy for the unlicensed FH systems [24]. To abide by the FCC regulation on the maximum channel occupancy, the authors in [22] provide an approach called adaptive frequency rolling (AFR). In AFR, adjacent networks hop over channels in a time-constrained manner choosing from the non-overlapping hopsets that are subsets of the total allowable channels. The regulation on the minimum hopset size is still disregarded on the ground that the coexistence of more than 5 FH networks leads to serious throughput degradation. In addition, to combat frequency-static interference, AFR with frequency probing is suggested, which cannot guarantee FCC compliance during the probing period. Hence, the quest for a coexistence scheme that not only handles potential interference, but also meets both of the FCC regulations remains unsated.

Another shortcoming of existing FH schemes for mutual coexistence is the need for inter-network communications and/or global parameters. In [23], for example, a collaborative way to solve both mutual interference and frequency-static interference is proposed where proximate networks exchange their load information with each other frequently. Obviously, this solution assumes static networks and incurs additional overhead and complexity for the collaboration. In [16, 22], the size of a hopset, $H$ and the duration of dwelling over a hopset, $T$ are global
Table I. A comparison among protocols on mutual interference

<table>
<thead>
<tr>
<th>Protocols</th>
<th>Reducing noise and static interference</th>
<th>Reducing mutual interference</th>
<th>Obeying FCC regulations</th>
<th>Avoiding global parameters or network collaboration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptive frequency hopping (AFH) [3,12–14]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Orthogonal grouping of channels [15]</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Frequency rolling [16]</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Dynamic adaptive frequency hopping (DAFH) [17,18]</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes†</td>
</tr>
<tr>
<td>Enhanced DAFH [19]</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes†</td>
</tr>
<tr>
<td>Adaptive frequency rolling (AFR) [22]</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes†</td>
<td>No</td>
</tr>
<tr>
<td>Collaborative channel segmentation [23]</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes†</td>
<td>No</td>
</tr>
<tr>
<td>The proposed DGH scheme</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes‡</td>
<td>Yes</td>
</tr>
</tbody>
</table>

†DAFH does not strictly follow the FCC regulation on hopset size, rather it follows an author-defined “etiquette rule.” As described by the authors, it is “highly likely” to follow the FCC regulation.
‡The authors use a modified constraint to limit the maximum channel occupancy where the maximum hopset size is 13. This modified constraint becomes weaker than the original FCC regulation when the hopset size is bigger. Please refer to Section 3.3 for further details.

parameters. To illustrate the consequence of such assumptions, the following scene is sketched: two Bluetooth piconets are using some fixed values for $H$ and $T$, and a new mobile piconet (e.g., a person using Bluetooth hand-free phone accessories) has just collocated with the existing systems. In this case, the third piconet either needs to know the predefined values for $H$ and $T$, or needs to communicate with the existing piconets to know the values. In practice, most FH systems are heterogenous and dynamic in nature. This motivates us to look for an autonomous hopset selection scheme.

1.2. Our Objective and Contributions

In this study, we address the problem of selecting dynamic hop sequences by proximate FH networks independently (i.e., without the need for inter-network communications) obeying current FCC regulations in the unlicensed spectrum concerning both the minimum size of a hopset and the maximum duration of channel occupancy. The objective is to maximize the number of effective coexisting networks that avoid mutual interference along with noise and frequency-static interference. We propose a scheme termed as dynamic Gaussian hopping.
(DGH). In DGH, FH networks change hopsets in parallel and perform Gaussian frequency selection from hopsets without violating both of the FCC laws. A comparison among DGH and other approaches is presented in Table I, where we particularly focus in approaches for mutual coexistence, rather than approaches for frequency-static interference (e.g., papers addressing interference between Bluetooth and WLAN networks). We simulate our approach to verify its performance, comparing it with recent approaches with regard to channel collision rate, goodput per network, fairness in channel usage, and the worst case delay for transmitting a packet.

The remainder of the paper is organized as follows. Section 2 discusses the frequency hopping system model, Section 3 describes details of our approach, Section 4 presents simulation results, and Section 5 concludes the work.

2. SYSTEM DESCRIPTION

The DGH scheme suggested in this paper is applicable to any FH systems. However, for explanation purposes, the rest of the description is oriented from the perspective of the widely used Bluetooth systems [3, 25].

Bluetooth is a standard aimed for short-range (10 m, in most applications) inexpensive wireless communication devices operating in the industrial, scientific, and medical (ISM) band. In the USA and most European countries, 79 radio frequencies of 1 MHz width are defined as communication channels in the 2.4 GHz band (we use “channel” and “frequency” interchangeably). The basic network configuration in Bluetooth systems is called the piconet, which is a star topology composed of one master device and up to seven active slave devices. The slaves can communicate with the master only. However, a device may be a member of multiple piconets, thus forming connected piconets (called a scatternet).

The communication in a piconet uses the time division multiplexing (TDM) technique. Each time-slot is 625 µsec, resulting in $\frac{1}{625} \mu \text{sec} = 1600$ slots/second. Transmission occurs in packets that occupy 1, 3, or 5 consecutive slots. Each packet is transmitted on a different hop frequency with a maximum frequency hopping rate of 1600 hop/second for packets occupying 1 slot and a minimum hopping rate of 320 hop/second for packets occupying 5 slots. That is, for single-slot messages, the transmission channel is changed at every slot; but for multislot messages, the channel used in the first slot is continued for multiple slots until a message is transferred. The channel hopping sequence is generated pseudo-randomly from the address and clock of the master of a piconet, and all slaves of the piconet are synchronized accordingly. A master always transmit in even slots, slaves transmit in odd slots, and only one device can transmit in a slot. Consequently, intra-piconet communications are collision-free.

Using the above method, different piconets operate according to their own hopping sequences. Since proximate piconets are not necessarily synchronized, the slot-starts in different piconets are random and a slot in a piconet may overlap with two slots in another piconet [8, 18]. If two devices transmit packets using the same frequency in overlapping slots, a collision occurs. For simplicity, we assume that a collision damages all packets involved even if the overlapping is partial [9, 22, 26, 27]. This is the worst case scenario of interference, since it does not model the effects of propagation to alleviate interference as in [28, 29]. We assume that the number of coexisting networks may change dynamically and their arrivals and departures follow a Poisson distribution.
In the rest of the paper, the term “hopset” and “hopping space” have different meanings. A “hopset” denotes a subset of channels from the total available channels. A “hopping space” denotes the area along which a hopset changes with time (in the time-frequency graph, as shown in Fig. 1).

The main idea for spectral coexistence is to parallelize the scope of the spectrum selection in collocated FH systems. First, hopsets in different systems are selected in such a way that the interference is minimized; then, these hopsets are changed in parallel at a constant rate, $r$. 

Figure 1. An example of parallel hopping spaces among coexisting networks

Figure 2. The adaption of hopping spaces

3. SOLUTION APPROACH
to avoid future interference. Fig. 1 illustrates the spectral coexistence for three FH networks \(a\), \(b\), and \(c\) over the 79 channels in the 2.4 GHz band.\(^1\) Initially, each network chooses its hopset starting at a random position (Section 3.1 describes how to resolve conflicts, if any). At a particular time \(t\), the hopset of Network \(a\) (denoted as \(H_a\)) dwells on frequency range 16–31; the hopset of Network \(b\) (denoted as \(H_b\)) dwells on frequency range 32–53; and the hopset of Network \(c\) (denoted as \(H_c\)) dwells on frequency range 59–79. After one slot time \(\Delta t\), each network changes its own hopset by two channels: removing one “lower” channel and adding one “higher” channel. The channels in a hopset roll over the complete set of 79 channels. As a result, at time \(t + \Delta t\), \(H_a\) dwells on frequency range 17–32, \(H_b\) dwells on frequency range 33–54, and \(H_c\) dwells on frequency range 60–1. Note that we do not assume that the coexisting networks are time-synchronized to each other, but they change their hopsets at the constant rate, \(r = 2\) channels/time-slot. The value of \(r\) is independent of the number of coexisting networks and load in each network. Hence, without any inter-network message exchange, networks can change their hopsets in parallel even though they are not time-synchronized and their time-slots may begin at different time instances.

In a Bluetooth piconet, each transmission slot is 625 \(\mu\)sec and a packet can occupy 1, 3, or 5 slots. For the 1-slot case, one carrier frequency is chosen from the hopset at each slot. After the slot duration, the hopset is changed such that one frequency is removed from the hopset and another frequency is added to the hopset. A frequency is chosen randomly from the new hopset for the next transmission slot. In this way, the hopset is kept changing at rate, \(r = 2\) channels/625 \(\mu\)sec. For the 3-slot or 5-slot cases, the hopset can be changed at rate of 6 or 10 frequencies per transmission, thus effectively achieving the same rate and yielding the desired parallelism of hopping spaces.

3.1. Adapting the Hopping Space

To identify channels that are “bad” to use (i.e., already occupied by others), an FH network can adopt any of the three methods: observing the packet error rate (PER), measuring the received signal strength indication (RSSI), and transmitting test packets [30, 31]. The last approach requires extra message communications. Although RSSI is more accurate than PER in assessing channels, RSSI consumes more power and occupies extra slots possibly from other functions [32]. That is why PER is becoming more prevalent now. Using PER, an FH network can segregate channels that experience more noise and frequency-static interference (as in the AFH scheme [12]). An IEEE 802.11 wireless LAN (WLAN) using the DSSS scheme typically remains fixed to a 22 MHz frequency band [30,31]. Hence, coexisting WLANs can be interpreted as frequency-static interference.

Once the “bad” channels are isolated, the remaining channels are called the available channels. If the number of available channels (denoted as \(H_{av}\)) is less than the minimum requirement by FCC (denoted as \(H_{min}\)), an FH network adds back some relatively less “bad” channels that were removed previously. We designate the \(i\)-th FH network as \(N_i\) (where \(i = 1, 2, \ldots\)). \(N_i\) chooses its hopset of any size from \(H_{min}\) to \(H_{av}\) and begins its hopping space at a position randomly chosen from \(H_{av}\). After operating for a threshold time \(T_{thr}\), PER for channels are calculated. If \(N_i\) is collocated with another FH network, PER may exceed the
acceptable limit (due to the frequency-dynamic mutual interference). In this case, \( N_i \) moves its hopping space (and hopping sequence) to another position randomly chosen from \( H_{av} \). This process continues until PER is acceptable for \( N_i \). Fig. 2 depicts how Network \( b \) moves its hopping space after experiencing interference with Network \( a \) that is already using the same hopping space at the same time. Network \( b \) starts operating at time \( t_1 \), but changes the hopping space at time \( t_2 \). Here, \( T_{thr} = t_2 - t_1 \). The probability of simultaneous change in the hopping spaces by both networks (experiencing a high PER for channels due to the mutual interference) is low, since the networks are not synchronized.

After achieving a stable hopping space, an FH network may continue to operate on that space as long as it does not experience any prolonged interference. Otherwise, it may invoke the reassessment of \( H_{av} \) by temporarily removing channels that have high PER and adding channels that have previously been kept out. The hopping space is adapted accordingly.

### 3.2. Shaping the Hopping

A network can choose a sequence of hopping frequencies from hopsets over the hopping space. An example of such a sequence is shown in Fig. 2 for Network \( a \) between time \( t_3 \) to \( t_4 \). At time \( t_3 \), the hopset of Network \( a \) is \( H_a \) and a frequency from \( H_a \) is chosen as a carrier frequency. After one time-slot (i.e., at time \( t_3 + \Delta t \)), the hopset changes to \( H_a' \) at rate \( r \) (as described earlier) and another carrier frequency from \( H_a' \) is chosen, and so on.

However, allowing a random choice with equal probability for all frequencies from a hopset size equal to or greater than \( H_{min} \) limits the number of fruitful coexisting FH networks to 5 [15, 16]. To accommodate more networks, we propose to shape the hopping of frequencies within the hopping space. The hopping space of each network has an axis as drawn in Fig. 3. The axis connects the frequencies in the middle of all hopsets over the space. The probability of selecting a frequency from a hopset is higher near the axis (or middle) and lower near the edges (or borders). That is, the probability distribution of frequency at each time-slot follows...
the normal (or, Gaussian) distribution with mean at the axis of the hopping space. This kind of frequency allocation enables hopping spaces among coexisting networks to be partially overlapped without much interference. As an example, Fig. 4(a) shows that two frequency hopping networks have their hopping spaces partially overlapped. However, as is evident from Fig. 4(b), the overlapping part shares the tail-ends of the two Gaussian distributions and, thereby, induces a reduced probability of selecting the same frequency by both networks. Furthermore, a complete overlapping of hopping spaces is also possible, given that networks are not time-synchronous. For the same hopping space and $H_{av}$, if different networks use non-overlapping hopsets at a particular instance of time, they will never interfere as they change hopsets at a constant rate, $r$. For example, at the instance of clock time 4 in Fig. 4(c), the hopset of Network $a$, $H_a$ and the hopset of Network $b$, $H_b$ are non-overlapping, even though their hopping spaces are completely overlapping. Since both networks consistently change hopsets at 2 channels/time-slot, they can safely coexist.

3.3. Conforming to FCC Rules

According to the FCC rules [24], FH systems operating in the 902–928 MHz band shall use at least 25 hopping frequencies (or 50 hopping frequencies, if the bandwidth of the hopping channel is less than 250 kHz) and the average time of occupancy on any frequency shall
not be greater than 0.4 seconds within a period of 10 seconds (or 20 seconds, respectively). FH systems in the 2.4–2.4835 GHz band shall use at least 15 hopping frequencies with the average occupancy time on any frequency not exceeding 0.4 seconds within a period of 0.4 seconds multiplied by the number of hopping channels employed. FH systems operating in the 5.725–5.850 GHz band shall use at least 75 channels with the average occupancy time on any channel not exceeding 0.4 seconds within a 30 second period. Let us say in general, given a frequency band, $H_{\text{min}}$ represents the minimum number of channels allowed in a hopset and $T_{\text{min}}$ represents the period for which 0.4 second occupancy/channel is allowed in that frequency band. For example, in the 5.725 GHz band, $H_{\text{min}} = 75$ and $T_{\text{min}} = 30$ seconds. In the 2.4 GHz band, $H_{\text{min}} = 15$ and, if a hopset of size 20 is used, $T_{\text{min}} = 20 \times 0.4 = 8$ seconds.

Let an FH network, $N_i$ operating in the 2.4 GHz band has $H_{\text{av}}$ available channels and is using $H$-sized hopsets. $N_i$ needs to ensure that $H \geq H_{\text{min}} = 15$ and no particular channel being used more than 0.4 seconds out of $T_{\text{min}} = 0.4 \times H$ seconds. In the DGH approach, the hopset rolls over all the $H_{\text{av}}$ channels in $H_{\text{av}} \times \Delta t$ time-unit, where $\Delta t$ is one slot duration. Let, one particular frequency be chosen $x$ times during this interval. In the worst case, $x = H$ since a frequency can be included in $H$ consecutive hopsets during this interval. In $H_{\text{av}} \times \Delta t$ time-unit, the occupancy of the frequency is $x \times \Delta t$ time-unit. Therefore, in $0.4 \times H$ seconds, the occupancy is

$$\frac{(x \times \Delta t) \times (0.4 \times H)}{(H_{\text{av}} \times \Delta t)} = \frac{0.4xH}{H_{\text{av}}} \text{ seconds.}$$

$N_i$ needs to check that

$$\frac{0.4xH}{H_{\text{av}}} \leq 0.4 \Rightarrow x \leq \frac{H_{\text{av}}}{H}.$$

That is, a particular frequency cannot be included more than $\frac{H_{\text{av}}}{H}$ times within consecutive $H$ slots (hence, $H_{\text{av}}$ slots) of the hopping sequence. For example, if $H_{\text{av}} = 63$ and $H = 15$, $x \leq \lceil 4.2 \rceil = 4$. Similarly, in the 902 MHz band, $x \leq \frac{0.4H_{\text{av}}}{10}$ for $H_{\text{min}} = 25$ and $x \leq \frac{0.4H_{\text{av}}}{20}$ for $H_{\text{min}} = 50$. In the 5.725 GHz band, $x \leq \frac{0.4H_{\text{av}}}{30}$. This constraint is true between consecutive sequences with or without a change in hopping space. A network can put this constraint when it selects hopping frequencies and, thus, engineer an FCC compliant hopping sequence.

### 3.4. A Simple Case Study

To understand frequency distribution and collisions in the proposed scheme, we analyze a simple case of two coexisting FH networks. Given that a network is already in operation, we find the probability of collisions in frequency selection when a new network is about to collocate. Since frequencies are discretely spaced in the spectrum, the probability of choosing a particular frequency from a hopset can be expressed as the probability mass function of a Poisson distribution with the parameter $\lambda$ set to the median value of the hopset. Due to the Central Limit Theorem, we can approximate the Poisson distribution by a Gaussian (or, normal) distribution with continuity correction [33, 34]. The probability density function of

---

‡In the 2.4 GHz band, $T_{\text{min}} = 15 \times 0.4 = 6$ seconds holds true only if the actual hopset size used is not greater than 15. Otherwise, the value of $T_{\text{min}}$ is higher. Therefore, the modified constraint used in [16, 22] cannot be used for hopset sizes greater than the minimum FCC requirement, $H_{\text{min}}$. 

Copyright © 2000 John Wiley & Sons, Ltd.  
*Int. J. Commun. Syst.* 2000; **00**:1–6  
Prepared using dacauth.cls
Figure 5. Analysis of collisions between two networks: (a) Overlapping of $i$ frequencies, (b) A given network and the range of frequencies where another network can collocate creating interference, (c) Two possible ways of overlapping $i$ frequencies.

Choosing a frequency, $f$ in the Gaussian distribution is

$$P(f, \mu, \sigma) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(f-\mu)^2}{2\sigma^2}}$$  \hspace{1cm} (1)$$

where $\mu$ is the mean value and $\sigma$ is the standard deviation. In our case, $\mu$ is the median value of current hopset. Let us assume for simplicity that the two networks under consideration use similar values for $\sigma$ and hopset size, $H$. For the Gaussian distribution, more than 99.99% of
the values lie within $\pm 4\sigma$ of the mean [34]. Hence, to achieve a hopping sequence normally distributed within the hopping space, we can use

\[
(+4\sigma) - (-4\sigma) = H
\]

\[\Rightarrow \sigma = \frac{H}{8}.
\]

In Fig. 5(a), the overlapping of $i$ frequencies between the hopsets of two networks is shown. We assign frequency-index as 1, 2, 3, ..., $H$ for each hopset as depicted. Let, $\mu_1$ and $\mu_2$ are the mean values of the two hopsets. A collision occurs if the same frequency $f$ is chosen in a particular time-slot by both networks. The probability of such a collision on $f$ is $P(index$ $of$ $f$ $in$ $the$ $first$ $hopset, \mu_1, \sigma) \times P(index$ $of$ $f$ $in$ $the$ $second$ $hopset, \mu_2, \sigma)$. Hence, the probability of collisions on the overlapping of $i$ frequencies is

\[
Pr(i) = P(1, \mu_1, \sigma)P(H - i + 1, \mu_2, \sigma) + P(2, \mu_1, \sigma)P(H - i + 2, \mu_2, \sigma) + P(3, \mu_1, \sigma)P(H - i + 3, \mu_2, \sigma) + \ldots + P(i, \mu_1, \sigma)P(H, \mu_2, \sigma).
\] (2)

The hopsets of two networks overlap if their mean values lie within $H$ frequencies away. In other words, collisions may occur if the hopset-median of a new network dwells within $\pm H$ frequencies (i.e., $2H$ range) of the hopset-median of existing network (as depicted in Fig. 5(b)). Assuming equal probability of collocating a new network in any of the available channels, $H_{av}$, the probability of locating the hopset-median of the new network in a particular frequency is $\frac{1}{H_{av}}$. As drawn in Fig. 5(c), there are two ways to overlap exactly $i$ frequencies between the two networks (here, $1 \leq i < H$). Therefore, the probability of two collocated networks to have an $i$-frequency overlap is $2H_{av}Pr(i)$. For $i = H$, there is only one way in which the two hopset-medians locate on the same frequency. Thus, the aggregated probability of collision between two networks during frequency allocation is

\[
\sum_{i=1}^{H} (Probability$ $of$ $i$ $- frequency$ $overlap) \times Pr(i)
\]

\[= \frac{2}{H_{av}}Pr(1) + \frac{2}{H_{av}}Pr(2) + \frac{2}{H_{av}}Pr(3) + \ldots + \frac{2}{H_{av}}Pr(H - 1) + \frac{1}{H_{av}}Pr(H).
\] (3)

where probabilities $Pr()$ are evaluated from the equation (2). Note that the equation (3) only considers two coexisting FH networks without implementing probing of frequencies (i.e., without segregating “bad” channels based on PER). Therefore, the probability of channel collision evaluated here can be considered as the upper bound for DGH.

4. PERFORMANCE EVALUATION

To examine the dynamic allocation of non-interfering spectral space among FH networks, we have developed a C++ language-based event-driven simulator. Along with the proposed DGH
Table II. Default settings for simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Bluetooth channels</td>
<td>79</td>
</tr>
<tr>
<td>Duration of one time slot</td>
<td>625 µsec</td>
</tr>
<tr>
<td>IEEE 802.11b occupancy</td>
<td>22 adjacent channels</td>
</tr>
<tr>
<td>IEEE 802.11b activity factor or traffic loading</td>
<td>70%</td>
</tr>
<tr>
<td>Bluetooth system loading</td>
<td>100% (7 active slaves)</td>
</tr>
<tr>
<td>Bluetooth packet types</td>
<td>DH1, DH3, DH5</td>
</tr>
<tr>
<td>Hopset size</td>
<td>15 channels</td>
</tr>
<tr>
<td>Hopping space changing threshold</td>
<td>5%</td>
</tr>
<tr>
<td>Probing threshold</td>
<td>50</td>
</tr>
<tr>
<td>Frequency remove threshold</td>
<td>50%</td>
</tr>
<tr>
<td>Frequency restore threshold</td>
<td>5 probings</td>
</tr>
<tr>
<td>Piconet density</td>
<td>16</td>
</tr>
<tr>
<td>Average piconet dwell time</td>
<td>80 seconds</td>
</tr>
<tr>
<td>Simulation time of one experiment</td>
<td>2000 seconds</td>
</tr>
</tbody>
</table>

scheme, we have implemented two other schemes: adaptive frequency rolling (AFR) [22] and adaptive frequency hopping (AFH) [12]. We have compared the results under various design parameters, network densities, and network types.

4.1. Performance Metrics

As described in [35], the performance analysis of coexisting systems using throughput (and/or goodput) is, in fact, superficial. Therefore, we adopt the more detailed measurement of overall channel collision rate as our main performance metric. Channel collision rate is the total number of collisions divided by the total number of hopping frequencies selected by the system. This computation directly indicates the efficiency of coexistence schemes in arbitrating channels among networks. However, to be complete, we also include the traditional goodput measurement. Goodput is defined as the number of useful bits per unit of time forwarded by a network, excluding overheads induced by the protocol and by the retransmission of lost or corrupt packets. To study the fairness in spectrum usage, we count the number of times channels are selected for transmission and show the standard deviations of usage in different coexisting schemes. We also use the worst case delay to observe the number of consecutive transmission slots that is attempted in the worst case to acquire a collision free channel for a particular packet transmission.

4.2. Simulation Settings

Unless mentioned otherwise, the simulation parameters have values as listed in Table II. In our simulation, each piconet has 100% traffic load between one master device and seven active slave devices. Three types of packets are used randomly for data transmission: DH1, DH3, and DH5 [3]. Each time slot is of 625 µsec. DH1 uses 1 slot for 1 byte of payload header and 27 bytes of payload data. DH3 uses 3 slots for 2 bytes of payload header and 183 bytes of payload data.
data. And DH5 uses 5 slots for 2 byte of payload header and 339 bytes of payload data. The total number of transmission channels is 79. The default hopset size is 15. As discussed in Section 3.4, we set standard deviation, $\sigma = \text{hopset size} / 8$ so that hopping frequencies are practically chosen from the current hopset.

The master device generates hopping sequence and maintains PER history. It performs the probing of hopping space to determine “good” and “bad” channels after 50 changes of the hopping sequence. During probing, a particular channel is temporarily removed from the hopping space if its PER is more than the frequency remove threshold, 50%. The channel is restored again after 5 such probings. Note that channel restoration is needed to avoid permanently marking a channel as a “bad” channel. A hopping space is relocated if more than 5% channels have higher PER values than the frequency remove threshold. The choice of default values for simulation parameters (e.g., hopping space changing threshold, probing threshold, frequency remove threshold, and frequency restore threshold) are justified in Section 4.3.2. The flowchart of steps followed by a piconet is given in Fig. 6. The average dwell time of a piconet instance (i.e., the lifetime of one arrival of a piconet) is 80 seconds. Once a piconet departs, it re-enters again at rate 0.999 so that the system is presumptively loaded
with the maximum number of piconets allowed for simultaneous dwelling. The default value of maximum piconets is 16 which is varied from 2 to 24 for different simulation experiments. To imitate the presence of the frequency static interference, a 22 channel-wide WLAN with 70% traffic load (or activity factor [7,19]) is used. Each experiment lasts 2000 seconds. The results are averaged and presented with 95% confidence interval.
4.3. Scenario without a WLAN

To study the performance of FH networks under mutual interference, we assume that neither a WLAN nor any other frequency static interference is present at this moment. We first evaluate the probability of channel collision for the trivial case as analyzed by the equation (3). For two FH networks with $H = 15$ and $H_{av} = 79$, the expected channel collision rate is 1.2656%. In simulation, for the same conditions, two FH networks in DGH experience 0.112% collision rate since DGH uses channel probing. Thus, probing reduces channel collision rate significantly (this rate is 0.172% and 1.006% in AFR and AFH, respectively).
4.3.1. Comparison with AFR and AFH

In general, a greater number of coexisting Bluetooth piconets results in increased mutual interference. Fig. 7 shows this observation when the piconet density is varied from 2 to 24 while other system parameters are kept constant at their default values. We find that Bluetooth networks under AFR suffer a lower packet collision rate than that under AFH, and Bluetooth networks under the proposed DGH scheme suffer a lower packet collision rate than that under AFR. The difference is more clear at higher densities. Accordingly, as Fig. 8 depicts, the goodput degradation is the least in DGH when the network density is increased. In other words, a DGH system can transmit the highest amount of useful data compared to the other systems.

In the AFH scheme, hopset size is the full range of available channels. In the AFR and DGH schemes, hopset sizes are not necessarily constant. In both schemes, the packet collision rate is lower for smaller hopset sizes. Fig. 9 indicates the trend when hopset size varies from 2 to 35 for 16 collocated piconets (all other simulation parameters use the default values as mentioned earlier, e.g., $\rho = 0.999$ and so on). Recall that a hopset of fewer than 15 channels is not recommended by FCC. Yet, we include the results to compare our approach with the AFR approach which supposedly performs well when hopsets contain fewer than 13 channels [22]. We find that if hopset size is smaller than 5, AFR has a lower collision rate. But if hopset size is higher than 5, DGH consistently outperforms. Similar performance is noticed with respect to goodput measurement (Fig. 10). The design of DGH permits more goodput realization for Bluetooths while operating in the desired range of hopset sizes as per FCC.

Another important inference that can be drawn from Fig. 11 is that when piconets in a system use independent hopset sizes (i.e., hopset size is not the same among coexisting piconets, which is a more likely behavior in a dynamic system), DGH performs better than AFR. This is true at different piconet densities with hopset size variation in ranges 2~13 and 15~35. In the 15~35 range (which is more desirable), the performance margin is higher. These results indicate that DGH can successfully achieve the necessary parallelism in frequency hopping even if hopset size is not a global parameter. At higher piconet densities and at greater hopset...
sizes, both the DGH and AFR schemes provide less productive accommodation.

We observe the fairness of channel usage among three schemes. Fig. 12 shows the standard deviation of the number of times channels are used (including attempts that result in collisions) at piconet density = 16 and hopset size = 15 (for AFH, hopset size is 79 before probing). A smaller standard deviation means that all channels are used almost equally (hence, good fairness). A larger standard deviation means that some channels are used more frequently than others (hence, poor fairness). We achieve the best fairness in DGH. The reason is that, unlike AFR, each piconet in DGH traverses the whole range of channels in each hopping sequence generation. Although each hopping sequence in AFH covers the same range as in
DGH, AFH is more random in frequency selection for hopping sequence and does not address the mutual interference. In Fig. 13, the channel usage histogram is drawn which further shows the divergence on the number of times channels are selected for data transmission. We find that AFR is less fair than AFH in channel usage since AFR selects channels from a smaller hopset for a longer period of time.

4.3.2. Properties of DGH To understand how DGH is affected by different system parameters, we test it under different settings. For example, Fig. 14 presents the relation between the probing threshold and the hopping space changing threshold. We find that the packet collision rate increases as the probing threshold increases. Similarly, Fig. 15 shows the effect of frequency adaption for DGH. The packet collision rate is lower when the frequency restore count is higher.
packet collision rate is the lowest if the threshold to change the hopping space is 5% and the threshold to probe is 50. This justifies why we use these values as the default values during the simulation.

As shown in Fig. 15, there is no apparent relationship between the frequency remove threshold and the frequency restore count. The packet collision rate is the lowest when the frequency remove threshold is 50%, but the collision rate remains almost the same for different settings of the frequency restore count. In our simulation, once a frequency is removed from the hopping space, it is restored after 5 probing.

Piconet density can be changed either by changing the maximum number of coexisting
Figure 18. Effect of WLAN coexistence

piconets or, by changing piconet arrival rate while keeping the other parameter fixed. We observe similar results in terms of packet collision rate and goodput for both cases. However, in Fig. 16, the worst case delay (i.e., the number of slots attempted in the worst case) to send a particular packet is given under different arrival rate (or load). As expected, the delay is higher at higher rate. Interestingly, the confidence interval (95%) appears greater for this measurement. This implies that the worst case delay can significantly diverge in different instances even though the average delay is steadily increasing with piconet density.

Finally, Fig. 17 shows how the changes in hopset size effect the $x$ value (please refer to section 3.3). Since these two parameters are inversely proportional, the bigger hopset is used, the lower $x$ value is calculated. A lower $x$ implies more restriction of the repetition of a particular frequency in the hopping sequence, which is necessary to enforce FCC laws.

4.4. Scenario with a WLAN

We also study the presence of frequency static interference on multiple collocated Bluetooths. We place a WLAN in a random position of Bluetooth channels. Assuming the WLAN occupies 22 channels and has a 70% activity factor, the packet collision rate versus piconet density follows the curvatures as in Fig. 18. Although the packet collision rate is higher here, we notice that the pattern is similar to the case without a WLAN (Fig. 7). Thus, the extra packet collision rate induced by the frequency static interference can be effectively reduced by the probing technique on the top of an intelligent coexistence scheme, which itself copes with the undergoing mutual interference.

5. CONCLUSION

We have proposed an easy-to-implement and effective coexistence scheme for frequency hopping systems. Our main contribution is the practicality of the approach in satisfying the two
Parallel and Gaussian Frequency Hopping for Dynamic Coexistence

regulations imposed by the Federal Communications Commission. We have neither used any global parameters, nor had the requirement of inter-network communications. In a distributed and adaptive manner, proximate networks choose parallel hopping spaces from which hopping sequences are generated using the Gaussian probability distribution. The proposed scheme allows partial and/or complete overlapping of hopping spaces and, thus, fits more networks than contemporary dynamic frequency hopping schemes. We justify the performance of the proposed scheme via details simulation comparing with other schemes.

REFERENCES

11. Bakker P. RF Interference in Home Networks. 3rd Twente Student Conference on IT, University of Twente, Netherlands, 2005.


