Adaptive Frequency Hopping for Bluetooth Robust to WLAN Interference

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***Abstract*—In this letter, we propose a new adaptive frequency hopping (AFH) scheme for Bluetooth to mitigate interference from IEEE 802.11x based wireless local area network (WLAN). To fast classify available channels for the Bluetooth, we first group the Bluetooth channels according to the channel allocation of WLAN and classify groups instead of Bluetooth channels. Then, we employ a moving average technique to estimate the status of Bluetooth channels in groups more accurately. The performance of the proposed scheme is verified by computer simulation. Simulation results show that the proposed AFH scheme significantly outperforms conventional schemes.**

***Index Terms*—Adpative frequency hopping, Bluetooth, wireless local area network.**

I. Introduction

Bluetooth is a short range wireless system operating in 2.4 GHz industry, society and medical (ISM) unlicensed spectrum band, where various types of radio systems can share the same resource. Bluetooth employs frequency hopping (FH) over 79 channels to mitigate interference from other radio systems using a pseudo-random FH technique [1]. It first generates a pseudo-random hop sequence based on its master clock and address, and then maps it into a desired hopping frequency so that each packet is transmitted through a different channel. Recent works have shown that Bluetooth with the use of pseudo-random FH may not provide desired performance in the presence of interference from coexisting radio systems such as IEEE 802.11x wireless local area network (WLAN) [2].

To alleviate this problem, a number of non-collaborative schemes have been suggested by means of two fundamental processes; channel classification and adaptive control process. The channel classification process estimates channel condition to detect the presence of interference source nearby. The adaptive control process mitigates the interference source by exploiting the information obtained from the channel classification process. IEEE 802.15 Task Group 2 (TG2) considers the use of an adaptive frequency hopping (AFH) scheme as one of such non-collaborative schemes. This AFH scheme minimizes co-channel interference by classifying channels based on the packet error rate (PER) and dynamically changing the hopping frequency [3]. However, it may not be effective in the presence of multiple WLAN interferers since it takes a long time to classify the status of each channel with an acceptable accuracy [4].

In this letter, we propose a new AFH scheme for Bluetooth by exploiting the spectrum characteristics of the IEEE 802.11x WLAN signal. To fast detect the channels that WLAN signal may exist, it first divides the Bluetooth channels in a number of groups according to the channel allocation of WLAN and identifies bad groups of channels yielding PER higher than a predetermined threshold. Then, it finely reclassifies the channels belonging to bad groups by applying a moving average (MA) technique to the channels in bad groups to prevent the channels without being interfered by WLAN among the channels belonging to bad groups removing from the hopping set.

The remainder of this letter is organized as follows. Section II describes the system model in consideration. The proposed AFH scheme for the mitigation of WLAN interference is described in Section III. The performance of the proposed scheme is verified by computer simulation in Section IV. Finally, conclusions are given in Section V.

II. System Model

A basic network entity in Bluetooth is a piconet (i.e., a star topology comprising a master and active slaves of up to seven). We consider N asynchronous Bluetooth piconets that work independently within the same coverage area and a pair of nodes which form an IEEE 802.11x based WLAN network. Assume that Bluetooth uses M channels for the signal transmission. Let π_i and B_i be the index and traffic load of the i-th piconet, respectively, λ be the traffic load of WLAN. It is assumed that when piconet π_i sends a packet through channels occupied by WLAN, the packet is transmitted with an error probability of λ [4].

Let $\mathbf{u_i}$ and $\mathbf{v}$ be a channel utilization vector of piconet π_i and WLAN, respectively, defined as

$$\mathbf{u_i} = \left[u_{i0}\ u_{i1}\ \cdots\ u_{i(M-1)}\right], \tag{1}$$

$$\mathbf{v} = \left[v_0\ v_1\ \cdots\ v_{M-1}\right] \tag{2}$$

where $u_{im} \in \{0,1\}$ and $v_m \in \{0,1\}$ for $m = 0, ..., M-1$. The value $u_{im} = 1$ denotes that channel m belongs to a hopping set of piconet π_i and $v_m = 1$ denotes that WLAN signal may occupy channel m.

III. Proposed Adaptive Frequency Hopping

In this section, we first analyze the PER of the Bluetooth system in heterogeneous operation environments, where multiple Bluetooth connections coexist with the presence of WLAN signal, and then propose an AFH scheme for the transmission in the presence of WLAN interference.

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A. Analysis of the Packet Error Rate

We first derive an analytic expression for the PER of a Bluetooth piconet. Let $p_i(m)$ be the probability that piconet π_i sends a packet through channel m, given by

$$p_i(m) = \frac{u_{im}}{M}. \quad (3)$$

and $A_{i,j}$ and A_i be an event that piconet π_i transmits its packets without being interfered by piconet π_j and any piconet, respectively. Since piconets transmit their signal in an asynchronous mode, it is likely that each packet sent by piconet π_i overlaps with two packets sent by piconet π_j in time. It can easily be shown that [5]

$$p(A_{i,j} | m) = (1 - B_j p_j(m))^2 \quad (4)$$

$$p(A_i | m) = \prod_{\substack{j=1 \\ j \neq i}}^{N} (1 - B_j p_j(m))^2. \quad (5)$$

Thus, the PER of piconet π_i through channel m can be represented as

$$\begin{aligned} \tilde{p}_i(m) &= p_i(m)\left(1 - (1 - \lambda v_m)(1 - q_n)\, p(A_i | m)\right) \\ &= \frac{u_{im}}{M}\left(\begin{array}{l} 1 - (1 - \lambda v_m)(1 - q_n) \\ \times \prod_{\substack{j=1 \\ j \neq i}}^{N} (1 - B_j p_j(m))^2 \end{array}\right). \end{aligned} \quad (6)$$

where q_n denotes the PER due to the channel noise and λv_m denotes the PER due to the WLAN interference with traffic load λ.

B. Mitigation of WLAN Interference

To transmit signal in the presence of WLAN interference, we exploit the spectrum characteristics of WLAN signal. When one of Bluetooth channels is occupied by the WLAN, it is highly likely that its adjacent channels are also occupied by the WLAN due to wideband characteristics of the WLAN signal. To fast detect the presence of WLAN signal, the master first divides the Bluetooth channels into K groups of channels corresponding to the number of WLAN channels and then classifies the status of each group based on the PER every T_L[1]. Assuming that the WLAN signal has a bandwidth of W (MHz) and the WLAN channels are separated by d (MHz), the channel set Ψ_k belonging to group k can be represented as

$$\Psi_k = \{ m \,|\, dk - 1 \le m \le dk - 1 + W \}. \quad (7)$$

for $k = 0, \ldots, K-1$. Then, the average PER of group k can be represented as

$$\tilde{p}_i^G(k) = \frac{\sum_{j=0}^{W} \tilde{p}_{i,k}(j)}{W+1}, \quad (8)$$

and a set of bad groups for piconet π_i can be identified as

$$\Lambda_i = \left\{ k \in V \,\middle|\, \tilde{p}_i^G(k) \ge \hat{q}_n \right\} \quad (9)$$

[1]After the Bluetooth has avoided the WLAN interference, it mitigates the interference from other Bluetooth piconets based on channel-by-channel classification method every $T_S(\le T_L)$.

where $\tilde{p}_{i,k}(j)$ denotes the PER of the j-th channel in group k of piconet π_i, $V = \{0, 1, ..., K-1\}$ and $\hat{q}_n$ denotes a maximal PER induced by channel noise. It is determined to prevent unnecessary channel removing due to the channel noise (e.g., $\hat{q}_n$ = 0.1). Assume that the WLAN signal is transmitted through channels in group $\hat{k}\,(\in \Lambda_i)$. It can be shown from (6) that the PER $\tilde{p}_i^G(\hat{k})$ of group $\hat{k}$ is given by

$$\tilde{p}_i^G(\hat{k}) = \frac{1}{W+1} \sum_{m=d\hat{k}-1}^{d\hat{k}-1+W} \left(\begin{array}{l} 1 - (1 - \lambda v_m)(1 - q_n) \\ \times \prod_{\substack{j=1 \\ j \neq i}}^{N} (1 - B_j p_j(m))^2 \end{array}\right) \quad (10)$$

and the PER of group $k (\in \Lambda_i)$ which may overlap with group $\hat{k}$ can be represented as

$$\begin{aligned} \tilde{p}_i^G(k) =& \frac{1}{W + 1 - d(k - \hat{k})} \\ & \times \sum_{m=dk-1}^{d\hat{k}-1+W} \left(\begin{array}{l} 1 - (1 - \lambda v_m)(1 - q_n) \\ \times \prod_{\substack{j=1 \\ j \neq i}}^{N} (1 - B_j p_j(m))^2 \end{array}\right) \\ & + \frac{1}{d(k - \hat{k})} \sum_{m=d\hat{k}-1+W}^{dk-1+W} \left(\begin{array}{l} 1 - (1 - q_n) \\ \times \prod_{\substack{j=1 \\ j \neq i}}^{N} (1 - B_j p_j(m))^2 \end{array}\right) \end{aligned} \quad (11)$$

where the first-term denotes the PERs of channels interfered by WLAN signal due to overlapping characteristics of WLAN channels and the second-term denotes the PERs of channels without being interfered by WLAN, respectively. Thus, if the Bluetooth piconet removes all channels belonging to group k, the channels without being occupied by WLAN (i.e., the second term in (11)) may be removed. Also, unlike IEEE 802.11b, since IEEE 802.11g has 6 OFDM null tones (i.e., about 3.5 MHz) as guard band on each side, the Bluetooth piconet should exclude the channels in guard band without being interfered by WLAN from bad groups. To this end, it needs to search an edge channel where the PER of channel changes most steeply. Hence, the Bluetooth piconet employs the MA technique to accurately detect this edge channel in bad groups, minimizing detection error by PER fluctuation of channels.

Let $G_{i,j}$ be the index of the j-th group in Λ_i. Then, the average PER through X (e.g., $X = W/2$) contiguous channels starting from the l-th channel in group $G_{i,j}$ can be represented as

$$\tilde{p}_{i,G_{i,j}}^{MA}(l) = \frac{\sum_{x=0}^{X-1} \tilde{p}_{i,G_{i,j}}(l + x)}{X}. \quad (12)$$

for $l = 0, \ldots, W/2$. Letting $c_{i,j}$ be the index of the $(W/2+1)$-th channel in group $G_{i,j}$, the set Θ_i of channels interfered by the WLAN among the channels belonging to bad groups can be determined as follows:

Step 1: Initialize.

$\Theta_i = \emptyset$ and j=1.

Step 2: Search the edge channel $\hat{m}$ where the PER of channel changes most steeply in group $G_{i,j}$ as

$$\hat{m} = \arg\max_{0 \le l \le W/2} \left(\tilde{p}_{i,G_{i,j}}^{MA}(l) - \tilde{p}_{i,G_{i,j}}^{MA}(l - X) \right).$$

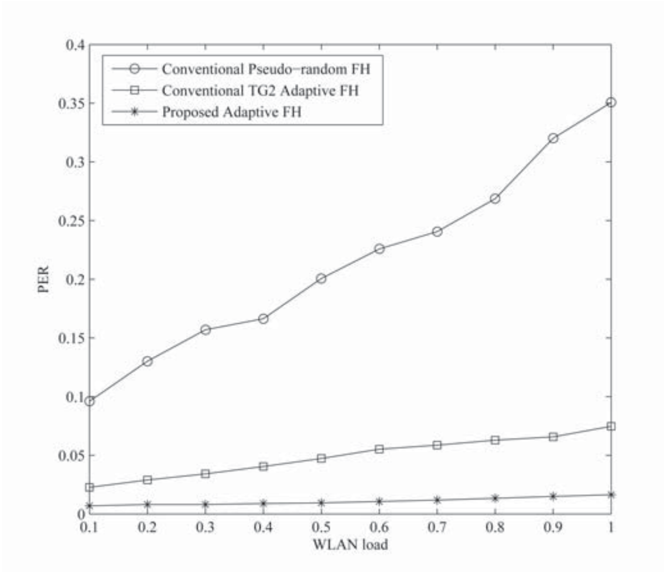

Fig. 1. PER according to the WLAN load.

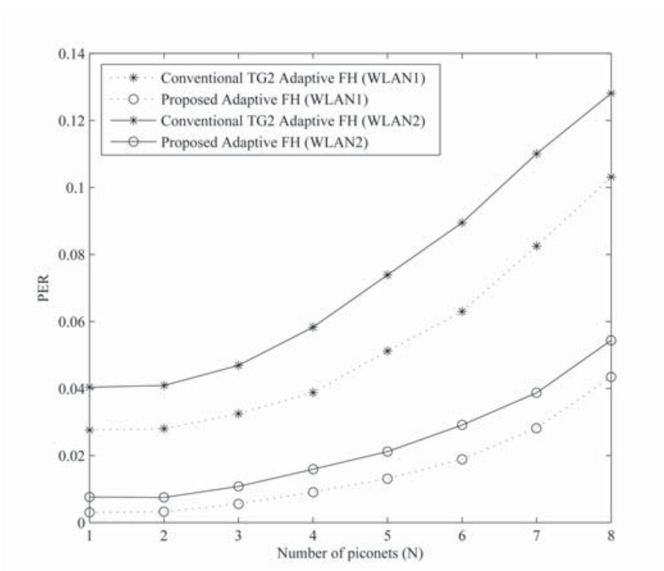

Fig. 2. PER according to the number of Bluetooth piconets.

Step 3: Check whether the channels from $(c_{i,j} - W/2) + \hat{m}$ to $(c_{i,j} + W/2) - \hat{m}$ are interfered by WLAN. If the number of channels between $(c_{i,j} - W/2) + \hat{m}$ and $(c_{i,j} + W/2) - \hat{m}$ having PER higher than $\sum_{m=0}^{M-1} \tilde{p}_i(m)/M$ is larger than δ (i.e., $\delta = (W - 2\hat{m})(W - d/W)$), then $\Theta_i \leftarrow \Theta_i \cup \{m\,|(c_{i,j} - W/2) + \hat{m} \leq m \leq (c_{i,j} + W/2) - \hat{m})\}$

Step 4: If $j < |\Lambda_i|$, then $j \leftarrow j + 1$ and go to step 2. Else stop.

Here, $|\Lambda_i|$ denotes the cardinality of Λ_i. Finally, the hopping set Φ_i of piconet π_i is determined as

$$\Phi_i = \{m\,|m \in \Omega - \Theta_i\}. \tag{13}$$

IV. Performance Evaluation

The performance of the proposed AFH scheme is verified by computer simulation. We assume an heterogeneous operation environment, where multiple Bluetooth connections coexist with the presence of IEEE 802.11b WLAN. We also assume that the distance between the master and slaves is 1 m, and that the transmit power of WLAN and Bluetooth is 25 mW and 1 mW, respectively. To verify the validation of the proposed scheme, we also evaluate the performance of two conventional schemes; conventional pseudo-random FH and TG2 AFH.

Fig. 1 depicts the PER of the proposed scheme when six Bluetooth connections coexist with the presence of a single WLAN signal with loading factor λ. It can be seen that the performance of the pseudo-random FH scheme is severely degraded as the WLAN load increases due to the use of blind hopping without consideration of interference. It can also be seen that the TG2 AFH scheme outperforms the pseudo-random FH scheme, but it still significantly suffers from the increase of WLAN load due to relatively slow estimation of interference. On the other hand, the proposed scheme is little affected by the WLAN interference since it can relatively fast estimate the WLAN interference.

Fig. 2 depicts the PER of the proposed scheme associated with the number of Bluetooth piconets in the presence of one or two WLAN signals. It can be seen that the proposed scheme is much less affected by the presence of multiple Bluetooth piconets compared to the TG2 AFH scheme even in the presence of two WLAN signals. This is mainly due to that the proposed scheme requires less estimation time for the channel classification than the TG2 AFH. Notice that the PER of the TG2 AFH scheme increases during the estimation time interval, since Bluetooth packets are sent through all the Bluetooth channels regardless of channel condition.

V. Conclusion

We have proposed a new AFH scheme for Bluetooth to avoid interference from WLAN. By dividing the Bluetooth channels into a number of groups according to the channel allocation of WLAN and then classifying bad groups of channels, the proposed scheme can significantly reduce to the time for the detection of channels that may be occupied by WLAN. Also, the channels without being interfered by WLAN among the channels belonging to bad groups can finely be detected by applying the MA technique to the channels belonging to bad groups, which results in less PER. The simulation results show the superiority of the proposed scheme even in the presence of two WLAN signals.

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