Transactions Letters

Mitigation of Co-Channel Interference in Bluetooth Piconets

Seung-Hwan Lee, Hyung-Sin Kim, *Student Member, IEEE,* and Yong-Hwan Lee, *Member, IEEE*

***Abstract*—In this letter, we consider the mitigation of co-channel interference in Bluetooth piconets. Prior to sending packets, the proposed scheme checks whether the next channel for the frequency hopping (FH) is in use by other signals or not. Then, it periodically detects busy channels subject to WLAN interference based on the packet error rate and interference signal detection rate in a group-wise manner and changes the set of hopping frequency. For further provision of channels for the FH, it maximized the number of channels for the FH by detecting additional channels which belong to groups classifies as being interrupted by WLAN, but not being used. The analytic design and simulation results show that the proposed scheme is quite robust to the presence of multiple WLAN and other Bluetooth signals, compared to the conventional mitigation schemes.**

***Index Terms*—Adaptive frequency hopping, Bluetooth, interference, 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. It can mitigate co-channel interference by means of pseudo-random frequency hopping (PFH) over 79 channels [1]. However, recent works have shown that the PFH may not work well in the presence of interference from coexisting radio systems such as IEEE 802.11x WLAN and other Bluetooth signals [2]-[5]. The IEEE 802.15.2 standard proposes several coexistence mechanisms, which can be categorized as collaborative or non-collaborative [2]. The collaborative mechanisms can be used when the WLAN and Bluetooth devices are integrated within the same physical unit and exchanging information between them is feasible. An alternating wireless medium access (AWMA) collaboratively coordinates Bluetooth and WLAN devices so that they transmit data alternately. A packet traffic arbitration (PTA) uses a central WLAN and Bluetooth arbiter that makes medium access decisions. An interference-aware scheduling scheme collaboratively coordinates the hopping frequency of collocated Bluetooth piconets by sharing the clock and address information of all adjacent piconet masters [3]. The collaborative coexistence mechanisms may be effective in collocated application scenarios. However, the collaborative mechanisms may involve limitation in its applications. In practice, since WLAN and Bluetooth devices are independently implemented and physically separated, it is nearly impossible for heterogeneous devices to exchange information.

In practice, the use of non-collaborative is often considered. To maintain the performance of Bluetooth piconet in the presence of co-channel interference, the transmit power is controlled based on the received signal strength (RSS) [4]. However, this power control may not provide desired signal-to-interference noise power ratio (SINR) when devices yielding interference to each other control the transmit power at the same time. Moreover, it may consume too much power when the Bluetooth device is close to the interfering device. The Bluetooth interference can be mitigated by means of orthogonal hop set partitioning (OHSP) [5], where Bluetooth piconet randomly chooses one of predefined five orthogonal FH sets each of which comprises a small number of channels (e.g., 15 or 16 channels). However, when collocated Bluetooth piconets use the same FH set, the use of OHSP may experience packet collisions much frequently than the use of PFH. The OHSP may not work well in the presence of WLAN signal since it does not consider the channel condition for the selection of FH set. To alleviate this problem, a number of two-step non-collaborative processing techniques have been considered, comprising channel classification and control process [6]-[10]. The Bluetooth specification considers the use of adaptive frequency hopping (AFH) [6]. It classifies channels subject to co-channel interference based on the packet error rate (PER) and then dynamically changes the hopping frequency. However, it may take a long time to detect the presence of interference source with an acceptable accuracy since it classifies all the channels individually, yielding noticeable PER performance degradation in the presence of multiple WLAN interference. It is also significantly affected by the presence of Bluetooth interference signals since the probability of collision with other Bluetooth interference signals increases as the number of channels for the FH decreases [7]-[10]. Interference source oriented AFH (ISOAFH) detects busy channels subject to WLAN interference based on the PER in a group-wise manner [7]. It is also effective in dealing with WLAN interference, but not effective in the presence of multiple collocated Bluetooth piconets. Since the frequency dynamic (FD) interference (e.g., other Bluetooth signal) occurs during a short time interval,

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The authors are with the Institute of New Media and Communications, Seoul National University, San 56-1 Shillim-dong Kwanak-Ku Seoul 151-742 Korea (e-mail: {leesh80, kimhs86}@ttl.snu.ac.kr).

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while the frequency static (FS) interference (e.g., WLAN signal) occurs during a considerably longer time interval, the use of bad channel removal strategy in the AFH-based interference mitigation scheme is not effective in the presence of FD interference. Thus, it may be desirable to fast classify only channels occupied by the WLAN interference signal and remove them from the FH set in the coexistence of multiple Bluetooth piconets and WLAN interference.

Recently, various schemes to ascertain the identity of the interference source have been proposed. Channels subject to Bluetooth or WLAN interference can be distinguished by employing a double threshold technique [8]. If the channel has a PER lower than a threshold determined by the average PER of whole channel, it is classified as a "clear" channel. If the channel has a PER higher than another predefined threshold (e.g., 0.5), it is classified as a "busy" channel occupied by the WLAN interference signal and then it is removed from the FH set. However, this technique may not detect the presence of WLAN interference when the traffic load of WLAN interference signal is lower than a predefined threshold since the collision probability with the WLAN interference is proportional to traffic load of WLAN interference [11]. The Bluetooth piconet may not know the traffic load of WLAN interference signal in a non-collaborative scheme, making it ineffective to classify the channel simply based on the PER. The presence of WLAN interference can be detected by identifying the total number of bad channels in the spectral region of WLAN interference signal or finding the band edge of WLAN signal [9], [10]. If the number of busy channels is larger than a threshold, all the FH channels in the spectral region of WLAN interference signal are classified as the busy channel and removed from the FH set [9]. However, the performance of this technique may rapidly deteriorates as the number of collocated Bluetooth piconets increases since it cannot utilize clear channels as many as possible, increasing the probability of collision with other Bluetooth interference signals. The lower and upper band edge of WLAN signal can be detected by finding the channel where the PER changes most steeply [10]. If the majority (e.g., 0.75) of channels in the lower and upper band edge have a higher PER than their left adjacent clear channels, all the FH channels in band edge are classified as the busy channel and removed from the FH set. However, it may not provide desired performance in the presence of overlapped or consecutive multiple WLAN signals. Although the coexistence mechansims previously introduced improve somewhat throughput performance of Bluetooth piconet, none of these resolve the packet loss problem of Bluetooth synchronous connection-oriented (SCO) link (i.e., voice connection) in the presence of WLAN or Bluetooth interferences. The packet collision with interference signals can cause the loss of voice packets. Since the Bluetooth SCO link such as HV1, HV2, HV3 does not support auto-matric repeat request (ARQ), lost packets are unrecoverable, which may significantly degrade voice quality. In this letter, we consider robust transmission of Bluetooth voice packet as well as data in the presence of multiple WLAN and Bluetooth interference signals. The performance can be improved by transmitting packets only when the channel is clear. Before transmitting packets, the proposed scheme checks whether the next FH channel is in use by other signal by means of carrier sensing. It also removes the channels occupied by WLAN interference signal from the hopping sequence through periodical channel classification process. To fast detect the presence of WLAN interference signal, it divides the available channels into a number of groups and then tests the availability of channels based on the PER and interference signal detection rate (ISDR) in a group-wise manner. Considering overlapped channel allocation of WLAN signals, it additionally identifies channels classified as a bad group, but not used by the WLAN signal with the aid of a non-linear processing technique.

The remainder of this letter is organized as follows. Section II describes the proposed scheme to mitigate co-channel interference. Section III verifies the performance of the proposed scheme by computer simulation. Finally, conclusions are given in Section IV.

II. Proposed AFH for Bluetooth Piconets

For robust transmission of Bluetooth voice packet as well as data in the presence of multiple WLAN and Bluetooth interference signals, a carriers sensing could be an effective option. Prior to sending packets, the proposed scheme first detects the availability of the next FH channel by means of carrier sensing. We consider the use of an energy detector for the carrier sensing. The Bluetooth transmitter detects the presence of interference on channel f_i through a simple hypothesis test, where f_i denotes the i-th channel in the FH set.

Let $\mathcal{H}_0$ and $\mathcal{H}_1$ denote the hypothesis corresponding to the absence and the presence of interference source, respectively. Then the received signal $r_{f_i}(l)$ through channel f_i can be represented as

$$\begin{aligned} \mathcal{H}_0 :&\ \ r_{f_i}(l) = n_{f_i}(l), \\ \mathcal{H}_1 :&\ \ r_{f_i}(l) = h_{f_i}(l) s_{f_i}(l) + n_{f_i}(l) \end{aligned} \tag{1}$$

where l is the sample index, $h_{f_i}(l)$ is the impulse response of channel f_i from the interference source to the transmitter, $s_{f_i}(l)$ is the signal transmitted from the interference source, and $n_{f_i}(l)$ denotes zero mean Gaussian noise with variance σ_n^2. Assuming the use of an energy detector, the master makes a decision on the existence of interference signal on channel f_i by

$$\varphi(f_i) = \begin{cases} 0, & y(f_i) < \lambda, \\ 1, & y(f_i) \geq \lambda \end{cases} \tag{2}$$

where λ is a threshold to be determined and $y(f_j)$ is the test statistic given by

$$y(f_i) = \frac{1}{L} \sum_{l=0}^{L-1} |r_{f_i}(l)|^2 \tag{3}$$

Here L is the number of samples. If the next channel for the FH is clear (i.e., $\varphi(f_i) = 0$), the transmitter sends packets through channel f_i. Otherwise, the transmitter simply skips the transmission through channel f_i. Letting $p_{\mathcal{H}_1}$ be the probability that the interference exists during sensing time τ, $p_{\mathcal{H}_1}$ in a symmetric mode (i.e., $T_s = T_s^u$) is given by

$$p_{\mathcal{H}_1} = 1 - \left(1 - \frac{\mu W N_W}{M}\right) \left[1 - \frac{B}{M}\left(\frac{T_{p,k} + \tau}{k T_s}\right)\right]^{N_B} \tag{4}$$

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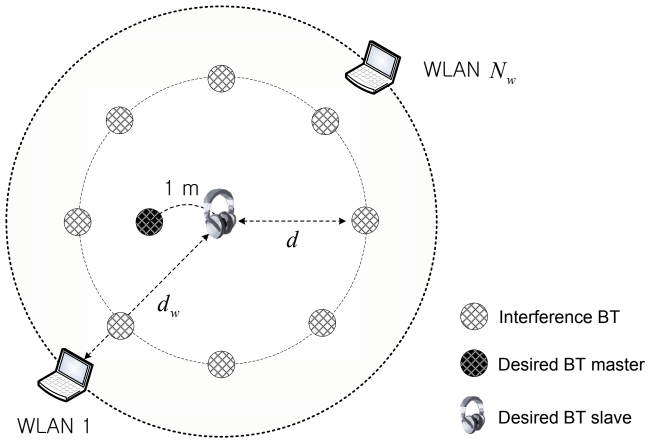

Fig. 1. Interference model within the coverage area

where N_W and N_B respectively denote the number of WLAN and Bluetooth interference, μ and B respectively denote the traffic load of WLAN and Bluetooth piconet, T_s and $T_{p,k}$ respectively denotes the duration of slot and k slot packet, T_s^u denotes the duration of uplink slot. Then, the achievable throughput of the proposed scheme can be represented as

$$R_{\mathrm{Pro}} = p_{\mathcal{H}_0}\left(1-p_f\right)\frac{N_{\mathrm{bits}}}{\bar{T}_{\mathrm{Pro},\mathcal{H}_0}} + p_{\mathcal{H}_1}\left(1-p_d\right)\frac{N_{\mathrm{bits}}}{\bar{T}_{\mathrm{Pro},\mathcal{H}_1}} \quad (5)$$

where $p_{\mathcal{H}_0} = 1 - p_{\mathcal{H}_1}$, and p_f and p_d are the false alarm and detection probability of the energy detector, and $\bar{T}_{\mathrm{Pro},\mathcal{H}_0}$ and $\bar{T}_{\mathrm{Pro},\mathcal{H}_1}$ respectively denote the average transmission time of packets in the absence and the presence of interference during sensing time τ, represented as

$$\begin{aligned}\bar{T}_{\mathrm{Pro},\mathcal{H}_0} &= 2kT_s + 2kT_s\sum_{j=1}^{\infty} j(q_k)^j\left(1-q_k\right)\\ &= \frac{2kT_s}{1-q_k},\end{aligned} \quad (6)$$

$$\bar{T}_{\mathrm{Pro},\mathcal{H}_1} = \frac{2kT_s}{1-{q'}_k}. \quad (7)$$

Here η denotes the instantaneous interference-to-noise power ratio (INR), q_k and q_k' denote the PER of k-slot packets associated with channel noise and interference, respectively. Then, the proposed scheme removes busy channels occupied by the WLAN signal from the hopping sequence as illustrated in Fig. 2.

For fast detection of busy channels occupied by the WLAN interference signal, the whole channel is divided into K groups of channels as

$$\Psi_k = \left\{m \,|Wk \le m \le W\left(k+1\right);\ \ k = 0,\ldots,K-1\right\}. \quad (8)$$

The proposed scheme tests the occupancy of each group of channels by the WLAN interference signal based on the PER and ISDR at time $t_{n(\ge 2)} = nT_L/2$. Assume that the transmitter performs the carrier sensing $C\left(t_{n-2},t_n,m\right)$ times and detects the interference $D\left(t_{n-2},t_n,m\right)$ times on channel m during time interval $[t_{n-2},t_n]$. Then, the ISDR of channel m and the average ISDR of group k can be represented as, respectively,

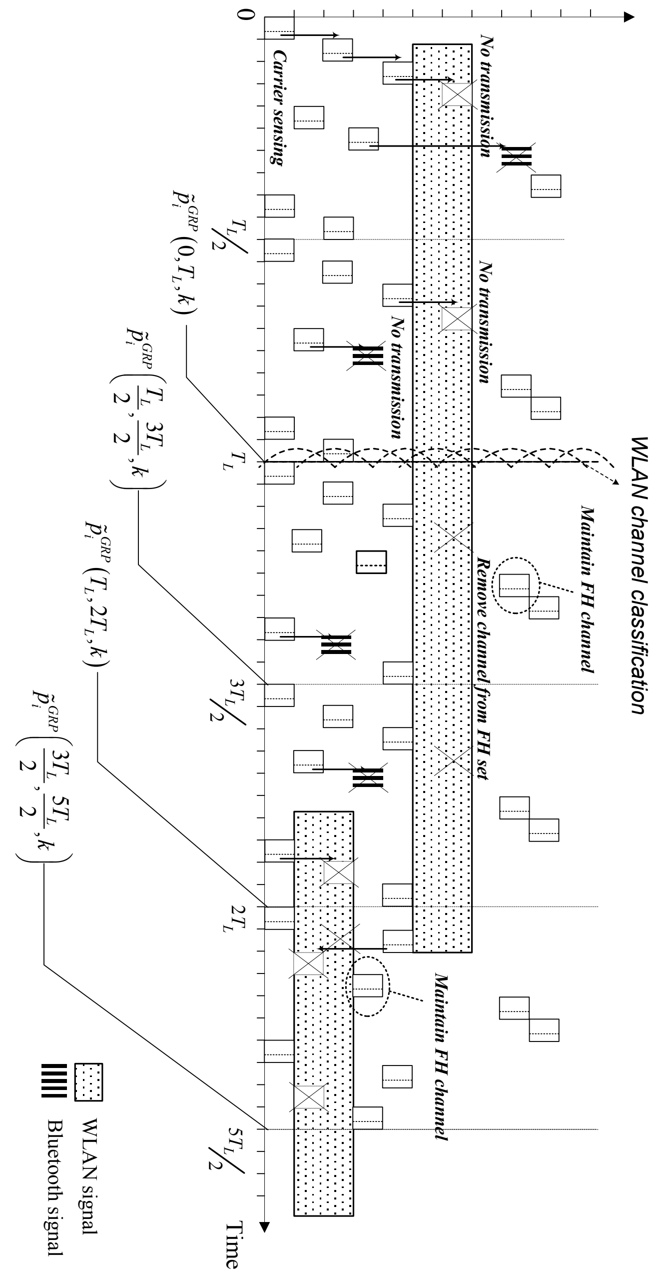

Fig. 2. Overall procedure of the proposed scheme

$$\phi\left(t_{n-2},t_n,m\right) = \frac{D\left(t_{n-2},t_n,m\right)}{C\left(t_{n-2},t_n,m\right)}, \quad (9)$$

$$\phi_{GRP}\left(t_{n-2},t_n,\ k\right) = \frac{\sum_{m=dk}^{dk+W}\phi\left(t_{n-2},t_n,\ m\right)}{W+1}. \quad (10)$$

Letting $\tilde{p}_{\mathrm{Pro}}\left(t_{n-2},t_n,m\right)$ be the PER of channel m during $[t_{n-2},t_n]$, the average PER of group k can be represented as

$$\tilde{p}_{GRP}\left(t_{n-2},t_n,k\right) = \frac{\sum_{m=dk}^{dk+W}\tilde{p}_{\mathrm{Pro}}\left(t_{n-2},t_n,m\right)}{W+1}. \quad (11)$$

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Then, the transmitter classifies a set of busy groups as

$$\begin{aligned}\Lambda \; = \; & \left\{ k \left| \tilde{p}_{GRP}\left(t_{n-2}, t_n, k\right) \geq \delta \right. \right\} \\ & \cup \left\{ k \left| \phi_{GRP}\left(t_{n-2}, t_n, k\right) \geq \delta' \right. \right\}, \\ & k = 0, \ldots, K-1. \end{aligned} \tag{12}$$

where δ' is a threshold to be determined. This process can fast detect the presence of WLAN interference in a group-wise manner (i.e., groups of busy channels). However, since the bandwidth of WLAN interference signal can be overlapped with that of other WLAN interference signals, the busy groups may include clear channels which are not actually occupied by the WLAN interference. Since it is desirable to use channels available for the AFH as many as possible, the proposed scheme finds out such clear channels belonging to the busy groups.

Since the PER or ISDR of channels occupied by the WLAN interference signal is usually higher than that of channels free from the WLAN interference, the PER or ISDR of channels is abruptly changed near the band edge of WLAN interference signal. Thus, the proposed scheme fast detects clear channels free from the WLAN interference by means of nonlinear filtering (e.g., order statistic filters) [12]. We consider the use of the median filter as a simple order statistic filter. Let ω_i be the index of the i-th group in Λ. Assumming that the channel spacing of WLAN interference signal is v (MHz), the set Φ_i of WLAN channels which overlap more than half of the bandwidth with ω_i can be represented as

$$\Upsilon_i = \begin{cases} \left\{ k' \left| 0 \leq k' < \left\lfloor \frac{W/2}{v} \right\rfloor \right. \right\} & \text{for } \omega_i = 0, \\ \left\{ k' \left| \left\lfloor \frac{(Wv_i - W/2)}{v} \right\rfloor \leq k' < \left\lfloor \frac{(Wv_i + W/2)}{v} \right\rfloor \right. \right\} \\ \text{for } 1 \leq \omega_i \leq |\Lambda|, \end{cases} \tag{13}$$

where $\lfloor x \rfloor$ denotes the largest integer number of smaller than or equal to x, and the set of Bluetooth channels which overlap with WLAN channel k' can be represented as

$$\Phi_{k'} = \left\{ m \in \Omega \left| vk' \leq m \leq vk' + W \; ; \; k' \in \Upsilon_i \right. \right\}. \tag{14}$$

Then, the master checks whether channel k' $(\in \Upsilon_i)$ is in use by WLAN signal or not. To this end, the master first gets the median filtered output $\mathrm{MD}_{\omega_i}(l)$ of L' channels starting from the l-th channel in $\Phi_{k'}$ as

$$\mathrm{MD}_{k'}(l) = \sum_{x=l}^{L'+(l-1)} Q\left(t_{n-2}, t_n, vk' + x\right) \tag{15}$$

where $Q\left(t_{n-2}, t_n, vk' + x\right)$ denotes a quatization bit of $\tilde{p}_{\mathrm{Pro}}\left(t_{n-2}, t_n, vk' + x\right)$ or $\phi\left(t_{n-2}, t_n, vk' + x\right)$ to reduce the implementation complexity of the median filter given by

$$\begin{aligned} & Q\left(t_{n-2}, t_n, vk' + x\right) \\ & = \begin{cases} 1, & \text{if } \tilde{p}_{\mathrm{Pro}}\left(t_{n-2}, t_n, vk' + x\right) > \delta \\ & \quad \text{or } \phi\left(t_{n-2}, t_n, vk' + x\right) > \delta' \\ 0, & \text{otherwise,} \end{cases} \end{aligned} \tag{16}$$

If $\mathrm{MD}_{k'}(0)$ and $\mathrm{MD}_{k'}(W - L')$ is larger than $L/2$, it verifies whether k' is occupied by the WLAN signal or not by comparing the next V median filtered outputs with $L/2$, where V denotes the number of samples for the verification. When the next V median filtered outputs are larger than $L/2$, the transmitter confirms that channels in k' are interrupted by the WLAN signal and updates the set of busy channels as

$$\Gamma \leftarrow \Gamma \cup \left\{ m \in \Omega \left| vk' \leq m \leq vk' + W; \; k' \in \Upsilon_i \right. \right\}. \tag{17}$$

Finally, the FH set $\Theta\left(t_n, t_{n+1}\right)$ is determined as

$$\Theta\left(t_n, t_{n+1}\right) = \left\{ m \left| m \in \Omega - \Gamma \right. \right\}. \tag{18}$$

It can be shown that the corresponding throughput of the proposed scheme can be represented as

$$\begin{aligned} & R_{\mathrm{Pro}}\left(t_0, t_K\right) \\ & = \frac{1}{K+1} \left(R_{\mathrm{Pro}}\left(t_0, t_2\right) + \sum_{n=2}^{K} R_{\mathrm{Pro}}\left(t_n, t_{n+1}\right) \right) \end{aligned} \tag{19}$$

where

$$\begin{aligned} R_{\mathrm{Pro}}\left(t_0, t_2\right) \; = \; & \frac{N_{\mathrm{bits}}}{2kT_s}\left(1 - q_k\right)\left(1 - p_f\right) \\ \times \; & \left(1 - \frac{\mu W N_W}{M}\right)\left(1 - \frac{T_{p,k} + \tau}{kT_s M}\right)^{N_B}, \end{aligned} \tag{20}$$

$$\begin{aligned} R_{\mathrm{Pro}}\left(t_n, t_{n+1}\right) \; = \; & \frac{N_{\mathrm{bits}}}{2kT_s}\left(1 - q_k\right)\left(1 - p_f\right) \\ \times \; & \left(1 - \frac{u\left(t_n, t_{n+1}\right)\mu W N_W}{M}\right) \\ \times \; & \left(1 - \frac{T_{p,k} + \tau}{kT_s \left|\Theta\left(t_n, t_{n+1}\right)\right|}\right)^{N_B} \end{aligned} \tag{21}$$

where

$$\left|\Theta\left(t_n, t_{n+1}\right)\right| = M - \left(1 - u\left(t_n, t_{n+1}\right)\right) W N_W \tag{22}$$

where $u\left(t_n, t_{n+1}\right)$ denotes the presence of WLAN interference in channels belonging to the FH set, represented as

$$u\left(t_n, t_{n+1}\right) = \begin{cases} 1 & \text{for } t_n = n' T_R \\ 0 & \text{otherwise} \end{cases} \tag{23}$$

III. Performance Evaluation

We verify the proposed scheme by computer simulation. We investigate both the data and voice link. As summarized in Table I, we assume that the DH1 packet for the data link is used, and the HV1 packet for the voice link is used. We evaluate the performance of seven representative coexistence schemes; power control [4], OHSP [5], conventional AFH [6], ISOAFH [7], Intelligent AFH (IAFH) [9], Clustering AFH (CAFH) [10]. In addition, the PFH scheme [1] also is referred for comparison.

Fig. 3 depicts PER fluctuation of Bluetooth voice packet in the presence of one WLAN and two collocated Bluetooth piconets nearby, where the PER is plotted every 100 msec. It can be seen that the PER of the conventional AFH schemes increases as the number of periodical channel classification process increases. It is mainly because the probability of packet collision with other Bluetooth signals increases as the number of channels available for the FH decreases. It can also be seen that the ISOAFH scheme suffers from the interference signals even after the channel classification process. It is mainly due to that some of the bad channels are still used to comply with the FCC regulations (i.e., the number of FH channels should be more than 20). Assuming that acceptable

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TABLE I
SYSTEM PARAMETERS

Parameters	Values
Bluetooth traffic load	1.0
WLAN traffic load	0.6 or 1.0
Bluetooth transmit power	1 mW
WLAN transmit power	25 mW
Bluetooth packet type	DH1, HV1
Noise level	-114 dBm
Noise figure	23 dB
Shadowing factor	8 dB
WLAN packet duration	1303 usec
Number of median filter tap (L)	3
Desired detection probability of the energy detector	0.999
Distance between Bluetooth master and slave	1 m
Distance from WLAN APs (d_w)	2 m
Distance from other Bluetooth piconets (d)	2 m
Channel classification interval (T_L)	400 msec
Bad channel restoration time interval (T_R)	4 sec
WLAN operating channel	6, 11

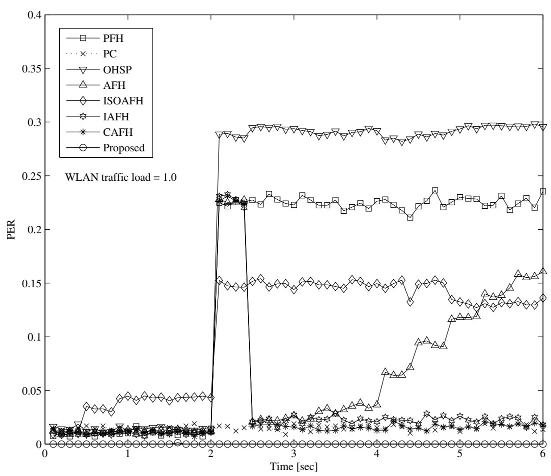

Fig. 3. Variation of the PER in heterogeneous operating environments.

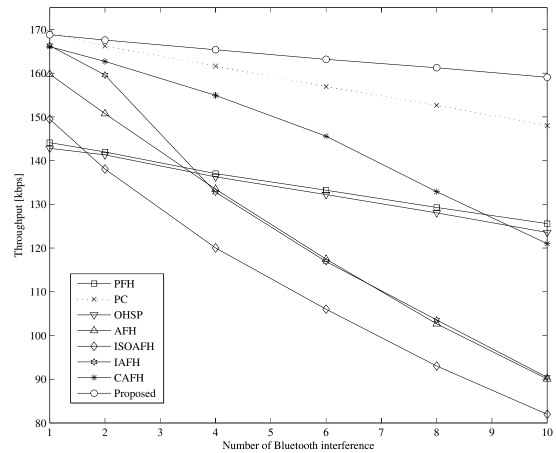

Fig. 4. Throughput associated with Bluetooth interference when $N_W = 1$ and $\mu = 0.6$.

PER of the Bluetooth voice packet is 1% [13], it can be seen that none of conventional schemes resolve the packet loss problem of Bluetooth SCO link in the presence of WLAN and Bluetooth interferences. On the other hand, it can be seen that the proposed scheme is little affected even in the presence of one WLANs and Bluetooth signals. This is mainly because the proposed scheme avoids packet collision with other interference signals by sending packets only when the channel is clear with the use of the proposed channel detection.

Fig. 4 compares compares the throughput of Bluetooth data packet associated with the Bluetooth interference in the presence of one WLAN interference. It can be seen that the performance of conventional AFH, ISOAFH and IAFH rapidly deteriorates as the Bluetooth interference increases. It is mainly because these schemes cannot utilize clear channels as many as possible, increasing the probability of collision with other Bluetooth signals as the number of Bluetooth interferences increases. On the other hand, it can be seen that the performance of CAFH scheme is somewhat less affected than others. This is mainly due to the fact that the CAFH can ascertain the identity of the interference source in the presence of one WLAN interference. It can also be seen that the proposed scheme outperforms the other schemes mainly because it can maximize the usage of FH channels by means of nonlinear filtering in addition to detection of busy channels.

Fig. 5 compares the throughput of Bluetooth data packet associated with the WLAN interference in the presence of five collocated Bluetooth piconets. It can be seen that the IAFH and ISOAFH are significantly affected by the WLAN interference mainly because the number of channels available for the FH significantly decreases as the number of WLAN interference increases. It can be seen that the OHSP scheme is not working well as the WLAN interference increases, mainly because it does not adapt the FH set according to the channel condition. It can also be seen that the throughput of the CAFH signficantly decreases in the presence of two WLAN interferences. It is mainly due to that it cannot ascertain the identity of the interference source well in the presence of overlapped or consecutive multiple WLAN signals. On the other hand, the proposed scheme is relatively less affected by the WLAN interference even in the presence of multiple Bluetooth interferences. It can also be seen that the PC scheme is little affected by the presence of multiple WLAN interferences, but it spends more transmit power (i.e., about 93 mW) than other schemes.

IV. CONCLUSIONS

We have considered the mitigation of co-channel interference in Bluetooth piconets such as Bluetooth. Prior to sending packets, the proposed scheme tests the availability of clear channels for the next FH by exploiting the nature of frequency dynamic and static interference signal. For fast detection, the proposed scheme periodically detects the interference based on the PER and ISDR in a group-wise manner. It also maximizes the usage of available channels for the FH by finding out channels free from the WLAN interference. The analytic and simulation results show that when the proposed scheme is

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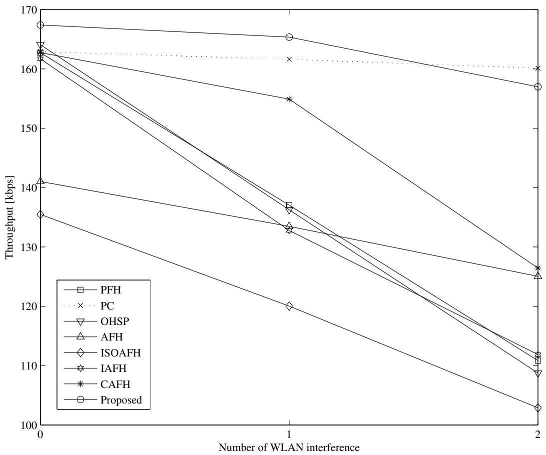

Fig. 5. Throughput associated with the WLAN interference when $N_B = 4$ and $\mu = 0.6$.

applied to the Bluetooth system, it works quite robust to the presence of multiple WLAN and other Bluetooth signals.

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