블루투스 시스템에서의 저연산량 스펙트럼 센싱에 관한 연구

*오동찬, **이용환
*서울대학교, **서울대학교
*mac81@ttl.snu.ac.kr, **ylee@snu.ac.kr

Low complexity spectrum sensing in Bluetooth

*Dong-Chan Oh, **Yong-Hwan Lee
*Seoul National Univ., ** Seoul National Univ.

요 약

In this paper, we propose a complexity reduced spectrum sensing scheme for Bluetooth to avoid the interference from other communication devices in 2.4 GHz ISM band. By exploiting the spectrum characteristics of interference sources, the proposed scheme detects the availability of channels by comparing the power spectrum density (PSD) with a threshold. To reduce the implementation complexity, the PSD is calculated by means of fast Fourier transform and linear interpolation. The threshold for the detection is determined to maximize the detection probability. To further improve the transmission performance, the proposed scheme dynamically changes the channels by measuring the transmission performance. Finally, the performance of the proposed scheme is verified by computer simulation in the presence of WLANs in the ISM band.

I. Introduction

Demand for ubiquitous multimedia services makes the use of wireless local area network (WLAN) and personal area network (WPAN) popular. IEEE 802.11x based WLAN has widely been deployed to support wireless services in a moderately sized area such as a small building or campus [1]. The use of Bluetooth and ZigBee is also widely spread out as an important element of WPANs. These WPAN and WLAN systems are often operating in unlicensed industrial, scientific, and medical (ISM) frequency band for low deployment cost. As a consequence, interference from coexisting other communication devices is unavoidable. Recent works have shown that the performance of Bluetooth piconet can severely be degraded due to interference from collocated piconets or other heterogeneous wireless devices [2] – [4]. Especially, recent measurement study reported that most of packet losses in a WPAN system are due to the interference from 802.11 WLAN [5].

For coexistence with other heterogeneous communication systems in 2.4 GHz ISM band, Bluetooth employs a pseudo-random frequency hopping (RFH) technique [6]. The RFH can mitigate interference by utilizing channels selected in a pseudo-random manner. However, it can only guarantee minimum packet error rate (PER) performance since it generates a hopping sequence without considering the signal characteristics of other communication systems in the ISM band. This problem can be alleviated by employing an adaptive frequency hopping (AFH) developed by Task Group 2 (TG2) in IEEE 802.15 [7]. The AFH is processed in a two-step manner; channel classification and adaptive control action. The channel classification estimates the channel condition to detect the presence of interference sources by measuring the packet error rate (PER). Adaptive control action mitigates interference sources based on the channel classification result. The AFH can outperform the RFH by only utilizing channels in good condition. However, it is required to blindly transmit packets for the channel classification, causing possible packet loss and PER performance degradation.

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Problems with the use of conventional RFH and AFH techniques can be alleviated by means of spectrum sensing. The spectrum sensing is often achieved by three types of detection techniques; energy detection, matched filter coherent detection, and cyclo-stationary feature detection [8]. Since non-coherent energy detection is simple and is able to quickly locate the spectrum occupancy information, it is widely used for the spectrum sensing. Previous works considered the energy detection by cooperating multiple radios [9], [10], but they can be applied to the detection of signals in a single channel. Signal detection in multiple channels can be achieved by estimating the power spectrum density (PSD) of a signal. The PSD of a wideband signal can be estimated by means of fast Fourier transform (FFT). The existence of interference can be detected by approximating the PSD of each channel as a Gaussian model [11]. However, it may take a long time to get a desired PSD from the FFT results. When applied to Bluetooth, it may need to perform FFT for all 79 channels, resulting in huge computational complexity.

In this paper, we propose a complexity reduced spectrum sensing scheme to detect the existence of WLAN signal. To reduce the processing complexity, the FFT is performed only on selected channels, not on all the channels. Moreover, the proposed scheme performs the FFT exactly once to accommodate rapidly time-varying wireless channel environments. The PSD of other channels can be estimated by a simple linear interpolation technique. The PSD of each channel is described by using a probability density function (pdf) of each channel condition (i.e., busy or idle). The threshold for the spectrum sensing is determined by a maximum a posteriori probability (MAP) criterion to maximize the detection probability.

The rest of this paper is organized as follows. Section

II describes the system model in consideration. The proposed scheme for the mitigation of interference is described in Section III. Section IV verifies the performance of the proposed scheme by computer simulation. Finally, conclusions are given in Section V.

II. System model

The received signal $r[n]$ in the time domain can be represented as

$$r[n] = s[n] + v[n] \quad (1)$$

where n denotes the sample index, $s[n]$ denotes the signal from other systems, and $v[n]$ denotes zero-mean additive white Gaussian noise (AWGN) with variance σ_v^2 (i.e., $v[n] \sim \mathcal{CN}(0, \sigma_v^2)$). The corresponding signal at channel k can be represented in the frequency domain by means of discrete Fourier transform (DFT) as

$$\begin{aligned} R[k] &= \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} r[n] e^{-j\frac{2\pi nk}{N}} \\ &= S[k] + V[k], \qquad k = 0, 1, \cdots, N-1 \end{aligned} \quad (2)$$

where $S[k]$ and $V[k]$ are the DFT of $s[n]$ and $v[n]$, respectively. Without loss of generality, it can be assumed that $S[k]$ and $V[k]$ are independent of each other. In what follows, we consider the use of FFT for the efficiency of computational complexity.

To decide whether channel k is occupied by other communication systems, consider the following simple hypothesis problem defined as

$$R[k] = \begin{cases} V[k] & , \mathcal{H}_{0,k} \\ S[k] + V[k] & , \mathcal{H}_{1,k} \end{cases} \quad (3)$$

where $\mathcal{H}_{0,k}$ and $\mathcal{H}_{1,k}$ denote the hypothesis corresponding to the absence (or idle state) and presence (or busy state) of other signal in channel k, respectively. For each channel k, the existence of other signal can be detected as

$$Y[k] \triangleq \left| R[k] \right|^2 \underset{\mathcal{H}_{1,k}}{\overset{\mathcal{H}_{0,k}}{\lesseqgtr}} \lambda . \quad (4)$$

III. Proposed Channel Sensing

To improve the channel sensing performance, we exploit the spectrum characteristics of interference sources operating in 2.4 GHz ISM band. Since most of packet losses in a WPAN system are due to the interference from 802.11 WLAN [5], we mainly focus on the mitigation of interference from WLAN in this paper. WLAN transmits signal having wider bandwidth than Bluetooth. If one of Bluetooth channels is interfered by WLAN, it is likely that adjacent channels are also interfered. By taking into account the characteristics of interference, we design a spectrum sensing scheme with reduced complexity.

It is desirable to detect the existence of interference signal before the signal transmission. It is known that receiver centric spectrum sensing schemes work better than transmitter centric schemes in cellular environments [12]. However, since the communication range of Bluetooth is much shorter than that of cellular systems, both the Bluetooth master and slaves experience similar interference effect. Considering the power consumption and processing protocol for the spectrum sensing, it may be practical to make the Bluetooth master perform the spectrum sensing.

The proposed scheme performs a single FFT process for selected channels to reduce the computational complexity. Before the FFT, it selects L Bluetooth channels equally separated by s_f channels; called selected channels. The master performs N-point FFT on the selected L channels as

$$R[s_f l] = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} r[n] e^{-j\frac{2\pi n s_f l}{N}} , \quad (5)$$

and calculates the PSD as

$$Y[s_f l] = \left| R[s_f l] \right|^2 \quad (6)$$

where $l = 0, 1, \cdots, L-1$.

The PSDs of the rest of channels, called unselected channels, can be estimated by means of interpolation. To reduce the complexity, we consider the use of a simple linear interpolator as [13]

$$Y\left[s_f l + i\right] = \alpha_i Y\left[s_f l\right] + \beta_i Y\left[s_f (l+1)\right] \quad (7)$$

where $i = 1, 2, \cdots, s_f - 1$, and α_i and β_i are scalar weights. Finally, the master compares the PSD of channels with a threshold value λ to decide the presence of interference. The PSD of all channels can be calculated by N-point FFT, requiring $(N/2)\log_2 N$ complex multiplications and $N \log_2 N$ complex addition. On the other hand, the proposed scheme requires $(N/2s_f)\log_2 N + 2(N-L)$ complex multiplication and $(N/s_f)\log_2 N + (N-L)$ complex additions for the PSD calculation. For example, when $N = 128$ and $L = 16$, the computational complexity is reduced by 59% and 78%, respectively.

The threshold value λ can be determined from the conditional pdf for each hypothesis. It can easily be shown that the PSD $Y[k]$ has conditional pdf for each hypothesis as

$$\begin{aligned} P_{Y[k]}\left(y_k \mid \mathcal{H}_{0,k}\right) &= \frac{1}{\sigma_v^2} \exp\left(-\frac{y_k}{\sigma_v^2}\right) \\ P_{Y[k]}\left(y_k \mid \mathcal{H}_{1,k}\right) &= \frac{1}{\sigma_v^2} \exp\left(-\frac{y_k + \left|S[k]\right|^2}{\sigma_v^2}\right) I_0\left(\frac{2\left|S[k]\right|\sqrt{y_k}}{\sigma_v^2}\right) \end{aligned} \quad (8)$$

where $I_0(\cdot)$ is a modified Bessel function of the first of order zero. The mean and variance of $Y[k]$ can be represented as, respectively,

$$E\{Y[k]\} = \begin{cases} \sigma_v^2; & \mathcal{H}_{0,k} \\ \sigma_v^2 + \left|S[k]\right|^2; & \mathcal{H}_{1,k} \end{cases} \quad (9)$$

$$\mathrm{var}\{Y[k]\} = \begin{cases} \sigma_v^4; & \mathcal{H}_{0,k} \\ \left(\sigma_v^2 + 2\left|S[k]\right|^2\right)\sigma_v^2; & \mathcal{H}_{1,k} \end{cases} \quad (10)$$

Under hypothesis $\mathcal{H}_{0,k}$, the false detection probability is

$$p_f(\lambda) = \exp\left(-\frac{\lambda}{\sigma_v^2}\right) \quad (11)$$

Similarly, under hypothesis $\mathcal{H}_{1,k}$, the miss detection probability is

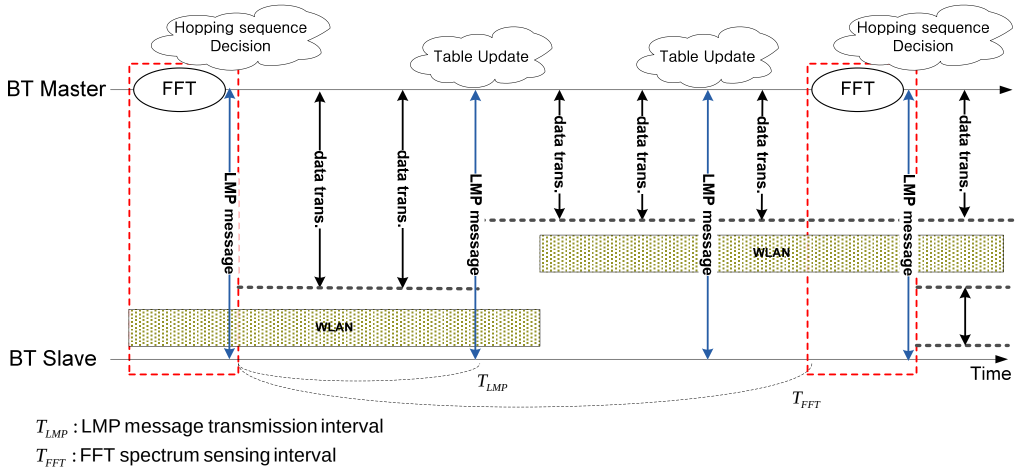

Fig. 1. Overall procedure of the proposed scheme

$$p_m(\lambda) = \int_0^{\lambda} \frac{1}{\sigma_v^2} \exp\left(-\frac{y_k + |S[k]|^2}{\sigma_v^2}\right) I_0\left(\frac{2|S[k]|\sqrt{y_k}}{\sigma_v^2}\right) dy_k \quad (12)$$

It can be shown from the (11) and (12) that the true detection probability for each hypothesis is

$$\begin{aligned} p_d(\lambda) &= 1 - p_m(\lambda); \quad \mathcal{H}_{1,k} \\ p_a(\lambda) &= 1 - p_f(\lambda); \quad \mathcal{H}_{0,k} \end{aligned} \quad (13)$$

We consider the use of a MAP criterion for the decision and determine the corresponding threshold value λ to maximize the detection probability. Using the Bays rule, the a posteriori probability can be represented as

$$\Pr\left(\mathcal{H}_{m,k} \mid Y[k]\right) = \frac{\Pr\left(Y[k] \mid \mathcal{H}_{m,k}\right)\Pr\left(\mathcal{H}_{m,k}\right)}{\Pr\left(Y[k]\right)} \quad (14)$$

where $\Pr\left(\mathcal{H}_{m,k}\right)$ is the a priori probability that channel k is occupied by interference signal and

$$\Pr\left(Y[k]\right) = \sum_{m=0}^{1} \Pr\left(Y[k] \mid \mathcal{H}_{m,k}\right)\Pr\left(\mathcal{H}_{m,k}\right). \quad (15)$$

Thus, the decision rule maximizing $\Pr\left(\mathcal{H}_{m,k} \mid Y[k]\right)$ is equivalent to maximizing $\Pr\left(Y[k] \mid \mathcal{H}_{m,k}\right)\Pr\left(\mathcal{H}_{m,k}\right)$. The decision rule is

$$\frac{\Pr\left(Y[k] \mid \mathcal{H}_{1,k}\right)\Pr\left(\mathcal{H}_{1,k}\right)}{\Pr\left(Y[k] \mid \mathcal{H}_{0,k}\right)\Pr\left(\mathcal{H}_{0,k}\right)} \underset{\mathcal{H}_{1,k}}{\overset{\mathcal{H}_{0,k}}{\lessgtr}} 1 \quad (16)$$

It can be shown from (8) that the decision rule (16) can be represented as

$$\left(\frac{p_I}{1-p_I}\right)\exp\left(-\frac{|S_k|^2}{\sigma_v^2}\right) I_0\left(\frac{2|S[k]|\sqrt{y_k}}{\sigma_v^2}\right) \underset{\mathcal{H}_{1,k}}{\overset{\mathcal{H}_{0,k}}{\lessgtr}} 1 \quad (17)$$

where the threshold value λ can be determined as

$$\lambda = \left[\frac{\sigma_v^2}{2|S[k]|} I_0^{-1}\left\{\left(\frac{1-p_I}{p_I}\right)\exp\left(\frac{|S[k]|^2}{\sigma_v^2}\right)\right\}\right]^2. \quad (18)$$

By comparing each estimated PSD with λ, the master determines whether the channel is idle or busy. After finding empty channels, the master generates an FH sequence for 32 empty channels.

Packet losses can occur due to sudden appearence of interference signal. This problem can be alleviated by means of dynamic packet transmission based on a channel-by-channel classification method [14]. In this method, slaves in the Bluetooth piconet estimate the PER for each channel. If the PER of a specific channel is higher than a desired PER, the slave requests the master to change this channel by using a link management protocol (LMP) message periodically sent with a period of T_{LMP}. Thus, the proposed scheme can transmit packets through good channels while avoiding blind transmission as in the conventional RFH and AFH. The overall procedure of the proposed scheme is shown in Fig. 1.

Table 1. Common simulation parameters

Simulation parameters	Setting
Bluetooth master location	(1,0) (m)
Bluetooth slave location	(0,0) (m)
Bluetooth transmit power	1 mW
Bluetooth packet type	DH1 for data ACL link, HV3 for voice SCO link
LMP message transmission interval (T_{LMP})	1000 packets
FFT spectrum sensing interval (T_{FFT})	10000 packets
FFT size	128
Number of selected frequency	16
WLAN source location	(0,d), d=1~5 (m)
WLAN transmit power	25 mW
Noise level	-114 dBm [15]
Noise figure	23 dB [15]

IV. Performance Evaluation

The performance of the proposed scheme is verified by computer simulation. The common simulation parameters are summarized in Table 1.

Fig. 2 depicts the PER performance of the proposed Bluetooth system in the presence of one or two IEEE 802.11b WLANs with various offered load factors at distance 2 m. It can be seen that as the offered load of WLAN increases, the proposed scheme can provide high performance gain over the conventional scheme. It can also

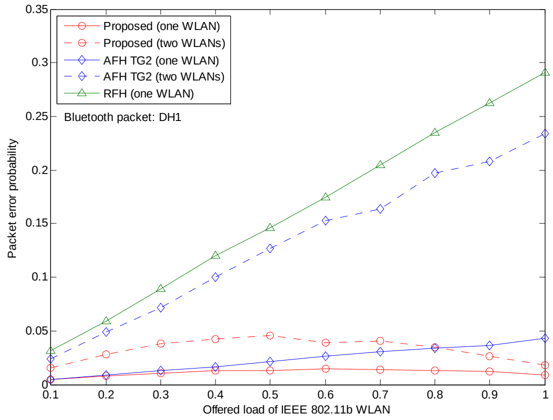

Fig. 2. PER performance of the proposed scheme

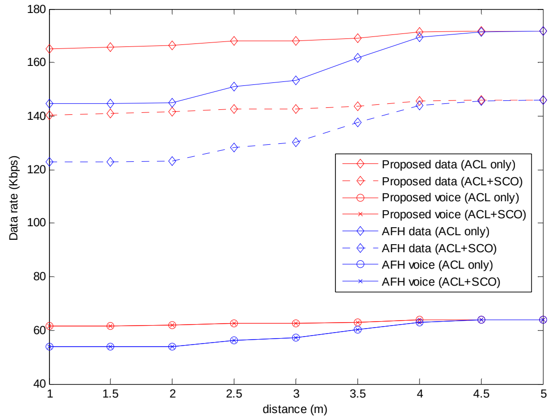

Fig. 3. Data rate of the proposed scheme

be seen that the PER of the proposed scheme is maximum when the activity of WLAN is medium. This can be explained as follows. When the activity of WLAN at channel k is q, the Bluetooth master transmits packets through this channel with probability $1-q$. Thus, the probability that Bluetooth packets collide with the WLAN signal is proportional to $(1-q)q$. As a consequence, the PER of the proposed scheme has a peak when the offered load of the WLAN is 0.5. However, the proposed scheme still significantly reduces the PER.

Fig. 3 depicts the transmission rate of the proposed Bluetooth system when two WLANs with offered load 0.7 are working at distance d. It can be seen that the conventional AFH schemes is not working well when the distance is less than 4 m, but the proposed scheme is little affected. It can also be seen that the data throughput is reduced when both voice and data traffic are in service. This is due to the fact that the SCO link has a priority over the data transmission (i.e., the ACL can use only unused slots). As a consequence, the maximum achievable data rate of the ACL link is reduced from 172.8 Kbps to 148.1 Kbps due to the presence of an SCO link.

V. Conclusion

In this paper, we have proposed a complexity reduced spectrum sensing technique for Bluetooth to detect channels occupied by other communication devices in 2.4 GHz ISM band. By exploiting the spectrum characteristics of the interference source and measuring the transmission performance, the proposed scheme enables to utilize idle channels for the packet transmission. The simulation results show that the proposed scheme is quite effective even when the interference sources are very close to Bluetooth.

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