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# 블루투스 및 무선 LAN 시스템의 동시지원을 위해 Listen-Before-Talk 기법을 결합한 Adaptive Frequency Hopping 방식의 제안

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# The hybrid method of Listen-Before-Talk and Adaptive Frequency Hopping for coexistence of Bluetooth and WLAN

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## ABSTRACT

In bluetooth system, there are two kinds of interference. One is the frequency static interference, for example 802.11 direct sequence, the interferer uses fixed frequency band. Another is frequency dynamic interference, for example other piconets or 802.11 frequency hopping, the interferer uses dynamic frequency channel and cant be estimated. In this paper we introduce a novel solution of hybrid method of Listen-Before-Talk (LBT) and Adaptive Frequency Hopping (AFH) to address the coexistence of bluetooth and Direct Sequence of wireless local area network (WLAN). Before any bluetooth packet transmission, in the turn around time of the current slot, both the sender and receiver sense the channel whether there is any transmission going on or not. If the channel is busy, packet transmission is withdrawn until another chance. This is the LBT in Bluetooth. Because of asymmetry sense ability of WLAN and bluetooth, AFH is introduced to combat the left front-edge packet collisions. In monitor period of AFH, LBT is performed to label the channels with static interference. Then, all the labeled noisy channels are not used in the followed bluetooth frequency hopping. In this way, both the frequency dynamic and frequency static interference are effectively mitigated. We evaluate the solution through packet collision analysis and a detail realistic simulation with IP traffic. It turns out that the hybrid method can combat both the frequency dynamic and frequency static interference. The packet collision analysis shows it almost doubles the maximal system aggregate throughput. The realistic simulation shows it has the least packet loss.

***Index Terms***: bluetooth, 802.11, WLAN, WPAN, coexistence, listen-before-talk, adaptive frequency hopping, performance evaluation

## Ⅰ. Introduction

The 2.4-GHz Industrial, Scientific and Medical (ISM) band is poised for strong growth because of its almost global availability and its suitability of low cost radio solution, Two emerging wireless technologies: Wireless Personal Area Network (WPAN) and Wireless Local Area Network (WLAN) fuel the growth. WLANs, standardized by IEEE 802.11 committee, are designed to cover office or building as an extension of existing wired networks. The fundamental building block of network is Basic Service Set. It is composed of several wireless mobile station and one fixed access point. WLAN devices can operate at bit rate as high as 11Mb/s and can use either DSSS (Direct Sequence Spread Spectrum) or FHSS (Frequency Hopping Spread Spectrum) technique

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[1]. In the case DSSS system, signal symbol is spread with 11-chip Barker sequence and the bandwidth is roughly 22MHz. In FHSS system, hopping sequences span over 79 channels, each one 1 MHz. WLANs access the open air by Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [1]. The IEEE 802.15 committee is deriving WPAN standard based on Bluetooth foundation specification [2]. Bluetooth is a cable replacement technique. It provides inter-connection of device in users vicinity in range of 10m. Bluetooth can support bit-rate up to 1 Mb/s for asynchronous data and isochronous voice transmission. The basic architecture unit of bluetooth system is piconet. The piconet is composed of a master device and up to seven active slave devices at most. A slow FHSS scheme is used at physical level and the hopping frequency covers 79 channels, each channel being 1Mhz wide. Each piconet master chooses a different hopping sequence to minimize the interference from other piconets. The nominal hop dwell time is equal to 625us, which is termed slot. A Time Division Duplex (TDD) technique is used to transmit and receive data and voice in a piconet. The slots are centrally allocated by master and alternatively used by master and slave. Each packet transmission occurs at the beginning of slot.

The attractiveness of working in an ISM band is that no license is needed. The downside is that the band must be shared and potential interference tolerated. WLAN and WPAN are complementary techniques and their devices will likely come together or may come close at a desktop. Without further provision, they will interfere each other. On the other hand, many piconets may cover the same area. The different piconets may interfere one another also. This is termed multi-piconets interference. With increased transceiver sensitivity, the number of piconets that may interfere each other increases explosively. Therefore, coexistence of bluetooth and WLANs is one of the more vexing problems that must be addressed. There are two classes of coexistence mechanisms: collaborative and non-collaborative. The collaborative mechanism enables the bluetooth piconet and the WLAN system to exchange information between one another so that the two wireless networks negotiate to minimize mutual interference. On the contrary, non-collaborative mechanism does not need to exchange information between the two wireless networks.

Other bluetooth piconet, WLAN and Microwave oven are likely to be the dominant interferers to bluetooth in coming year [3]. The interference can be classified as two kinds. For bluetooth piconet, the interference from 802.11 DS system always occupies the fixed frequency band. The packet collisions can occur only at the fixed frequency band. This is termed frequency static interference. On the contrary, other bluetooth piconets and 802.11 FH systems perform frequency hopping in the same number of channel and frequency band. It is impossible to estimate where and when the packet collisions will occur. This is termed frequency dynamic interference. In 1998, Greg Ennis presented a paper to describe the impact of bluetooth on 802.11 DS system [4]. To response it, Jim Zyren introduced some modification to the model and developed a complete paper [5]. Their result shows the degree of interference is dependent on local propagation condition, density of bluetooth piconet, bluetooth piconet loading, as well as packet size of 802.11 DS. Harrtsen simulated the bluetooth performance in high density 802.11 DS environments and found bluetooth data link experience more degradation than speech link [6]. However, in his simulation, the interference of bluetooth to bluetooth is ignored. Stenfan Zurbes simulated the bluetooth performance of a large number of co-located piconets with WWW traffic model and found marginally link throughput degrade by interference [7]. A. Kameman, N. Ngolmie *et al* and V. Mitter *et al* studied the interference of bluetooth to WLAN and vice visa through signal power analysis, detail simulation and experimental measurement [8,9,17]. Their results shows that, when the distance between the bluetooth device and 802.11 device is less than 2m, there will be significant interference between them [8,9,17]. Some mechanisms, such as power control, packet scheduling, Time Division Multiple Access (TDMA) of bluetooth slots and 802.11 slots, Adaptive Frequency Hopping (AFH), and adaptive fragmentation of 802.11 packet were proposed to improve the coexistence of WLANs and WPANs [10~12]. However, the first TDMA method does not support SCO packet of bluetooth. The last two schemes need some rules to guide that is the optimal and cannot mitigate the frequency dynamic interference. A complex MEHTA Engine, which consists of Bluetooth baseband, IEEE 802.11b Media Access Control (MAC) module and it interface, was proposed to monitor traffic patterns of both systems and then controls the length and timing of a packet to transmit [13].

This paper proposes a novel hybrid method of Listen-Before-Talk and adaptive frequency hopping to avoid the interference from both WLANs and WPANs. Section 2 introduces the Listen-Before-Talk mechanism and the hybrid method. Section 3 presents an interference analysis of WPANs and WLAN. Section 4 describes a realistic simulation model and presents the simulation results. Finally, discussion and conclusions are given in Section 5.

## Ⅱ. Listen-Before-Talk in Bluetooth

In bluetooth piconet, the packet transmission of each piconet depends on the masters clock and frequency hopping sequences without any consideration of the state of other piconets and channels. In WLAN DS system, although it senses the channel before transmission, it cannot sense the bluetooth activities [14]. Packet collision occurs when the packets from different networks overlap in time and frequency [14].

The slotted structure of bluetooth makes it possible to introduce Listen-Before-Talk (LBT) mechanism into bluetooth. As shown in the upper panel of Fig. 1, in any state of bluetooth link controller, there is at least 230ms interval before the beginning of packet transmission in next slot [2]. We call it turn around time . The turn around time is used for bluetooth device to change from Rx to Tx mode and make the frequency synthesizer tune to the next channel frequency. It is quite long and it is possible to sense the next frequency channel in it. The lower panel of Fig. 1 shows the bluetooth with LBT mechanism, where the dash block with shadow denotes the sense window. Before packet transmission, a check of the next channel, simple energy sense and comparison with a preset threshold, is performed in turn around time of current slot by both the sender and receiver of packet. If the next channel is busy or become busy during the sense window, the sender simply cancels packet transmission, skips the channel, and waits for the next chance. Otherwise, the next slot is free for packet transmission. With a small detection time for channel overlap, the former packet dominates the channel until the end of packet transmission. LBT is performed in both ends, the receiver knows the operation of pending packet; whether it is withdrawn or not.

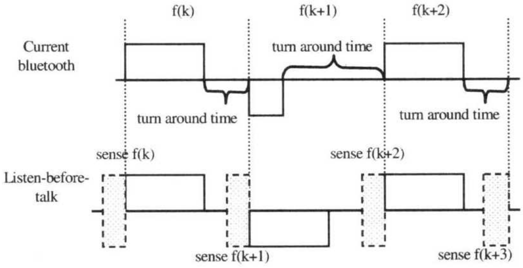

Fig. 1 Listen-Before-Talk mechanism in bluetooth

However, there are still some packet collisions between bluetooth and WLAN even after LBT. As shown in Fig. 2, there are two cases for bluetooth and WLAN packet collision. One is the bluetooth packet is ahead of the WLAN packet; another is the WLAN packet is followed by bluetooth. For bluetooth packet, the former case is termed trail-edge hit and the latter case is termed front-edge hit. Only the latter case of packet collision can be avoided by LBT. The remained packet collision can be contributed to asymmetry sense ability of WLAN and WPAN. The bluetooth can sense the activities of WLAN DS because WLAN signal power is strong and cover part of bluetooth channels. However, in general, WLAN cannot sense the activities of WPAN [14]. Compared with WLAN DS signal, WPAN signal is a narrow band signal. The frequency band of WLAN DS signal is usually 22MHz, whereas the bluetooth signal is only 1MHz [1,2]. Another reason is the WPAN signal power is low. Usually, the signal power of bluetooth is expected to be as low as possible [1,2].

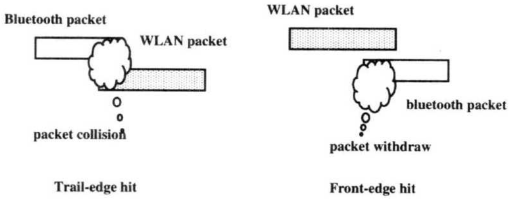

Fig. 2 Packet collision between WLAN DS and bluetooth

From the above analysis, we find the remained packet collision only comes from the WLAN DS packets. As we know, WLAN DS signal is static interference. Adaptive Frequency Hopping (AFH) is an effective method for this kind of interference [11,15]. AFH first monitors communication quality the channel and finds where is the interference. After labeled the channels as good or bad, AFH selects a new mapping sequence to avoid the known interference. AFH regularly revert to the original mapping mode to re-evaluates the channels [11].

Therefore, in this paper, we propose a new hybrid method of Listen-Before-Talk and Adaptive frequency hopping. The LBT senses transient availability of channel before packet transmission to combat the frequency dynamic interference. The AFH monitors long term availability of channel to combat the frequency static interference. In monitor period of AFH, LBT is performance in both sender and receiver in bluetooth. The bluetooth packet sink can distinguish packet withdraw and packet collision from packet source. If the packet loss of a channel is above a threshold, it is label as bad channels. After the monitor period, the bluetooth master and slaves exchange bad channel information and decide the final set of bad channels. In the next stage, all the labeled bad channels are not used in bluetooth frequency hopping.

## Ⅲ. Bluetooth Interference Analysis

In this part, we analyze the interference between bluetooth piconets and WLAN. We make several assumptions in analysis:

- All the bluetooth piconets and WLAN system are independent each other.

· All bluetooth piconets use the same packet type.

· Bluetooth device can sense any packet that appears in the sense window. Therefore, there is no hidden terminals in bluetooth with LBT.

· Any packet collision incurs packet loss.

Fig. 3 illustrates the timing of two bluetooth links. The bluetooth packets occur on a periodic basis. The bluetooth packets are transmitted with the period of $T$, and the transmission data packet sizes are $S_{Bi}$ and $S_{Bj}$ respectively. For single slot data packet, the $T$ is 1250us. For multi-slots data packet, the $T$ is 2500us and 3750us, respectively. The bluetooth packet size can be fixed or random depends on packet type and traffic model. Generally, different piconets are asynchronous. Here, we assume the intervals before the start of bluetooth packet, $X_{Bi}$, is uniform distribution as follow

$$X_{Bi} \sim U(0,T) \qquad (1)$$

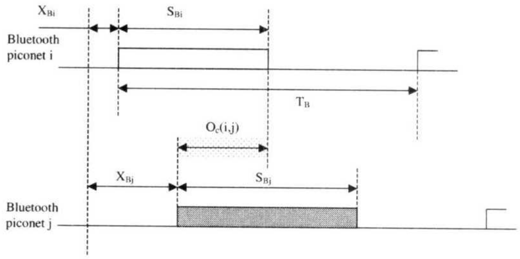

Fig. 3 Timing of two bluetooth packets from different piconets

The probability of bluetooth packet collision, $p_c(i,j)$, is the joint probability of packet overlap in both time and frequency, which is given by

$$p_c(i,j) = \frac{S_{Bi}+S_{Bj}}{T}\frac{1}{C} \tag{2}$$

where $C$ is the number of available channels. In bluetooth, $C$ is 79 in most of country [2]. We denote by $O_c(i,j)$ the overlap time size. A bluetooth packet does not collide with more than one packet from the same piconet since tow consecutive packets use different transmission channel. The value of $O_c(i,j)$ depends on packet start position and packet size. We distinguish five cases to compute $O_c(i,j)$

$$O_c(i,j) = \begin{cases} \min(S_{Bi}, S_{Bj}) & \\ \quad if \quad 0 = X_{Bi} - X_{Bj} & \\ \min(S_{Bi}, \max(0, X_{Bj} + S_{Bj} - X_{Bi})) & \\ \quad if \quad S_{Bi} - S_{Bj} \le 0 < X_{Bi} - X_{Bj} & \\ \min(S_{Bj}, \max(0, X_{Bi} + S_{Bi} - X_{Bj})) & \\ \quad if \quad X_{Bi} - X_{Bj} < 0 < S_{Bi} - S_{Bj} & \\ \max(0, X_{Bi} + S_{Bi} - X_{Bj}) & \\ \quad if \quad X_{Bi} - X_{Bj} < 0 \le S_{Bj} - S_{Bi} & \\ \max(0, X_{Bj} + S_{Bj} - X_{Bi}) & \\ \quad if \quad S_{Bj} - S_{Bi} < 0 < X_{Bi} - X_{Bj} & \end{cases} \tag{3}$$

The packet error probability depends on bit error rate (BER) of physical channel and Forward Error Code (FEC) of the overlap part, as well as $p_c(i,j)$. For example, if the overlap part has no FEC, the error probability is

$$e(BER, FEC, O_c) = 1-(1-BER)^{O_c} \tag{4}$$

If more than two packets collide together, the overlap part BER deteriorate due to stronger interference.

In all the $N$ piconets, the packet collision probability of a packet from *ith* piconets is given by

$$\overline{p}_c(i) = 1 - \prod_{j=1, j\neq i}^{N}(1-p_c(i,j)) \tag{5}$$

We denote by *WLBT* the size of LBT sense window. For the *ith* piconet, the packet withdraw probability is the probability of sense window overlap with the packet from the any other piconets. If we assume the LBT can sense any packet appears in LBT sense window, the packet withdraw probability of bluetooth with LBT, $p_w(i)$, can be written as follow

$$\overline{p}_w(i) = 1 - \prod_{j=1, j\neq i}^{N}\left(1-\frac{w_{LBT}+S_{Bj}}{T_B}\frac{1}{C}\right) \tag{6}$$

In the same way, the packet collision and packet withdraw between WPAN packets and WLAN packets can be analyzed. The overlap size of two packets collision can be computed using Eq. (2). However, the probability of a bluetooth packet and WLAN DS packet share the same frequency channel is 22/79, and a bluetooth packet may collide with more than one WLAN DS packets [1,2].

In bluetooth data link, the data packets are followed by an acknowledgement from the recipient in the opposite direction. Any packet errors in either packet enable ARQ mechanism to retransmit the packet. If we assume all the piconets are active, send the same size packet, and any packet collision incurs packet error, given the probability of packet collision and packet withdraw, we can obtain the aggregate throughput of $N$ piconets. For current bluetooth, the aggregate throughput of is

$$S = \rho N\left[\left(1-\frac{2*s_d}{T*C}\right)\left(1-\frac{2*s_a}{T*C}\right)\left(1-\frac{s_a+s_d}{T*C}\right)^2\right]^{N-1} \tag{7}$$

where $S_a$ and $S_d$ is the packet size of acknowledge packet and data packet, and $\rho$ is the payload information duty cycle. For bluetooth with LBT, if we assume all the piconet can hear each other, there will be no packet collision. Then, the aggregate throughput becomes

$$S_{LBT} = \rho N\left[\left(1-\frac{s_d+w_{LBT}}{T*C}\right)^2\left(1-\frac{s_a+w_{LBT}}{T*C}\right)^2\right]^{N-1} \tag{8}$$

The current bluetooth contents transmission in the whole slot time. However, for bluetooth with LBT, a channel is dominated by the former packet until the end of packet transmission. One packet collision may cause two packet losses in two different piconets. LBT only causes withdraw packet in one piconet. Therefore, the bluetooth system aggregate throughput increases after using LBT.

For bluetooth with AFH, the number of available channel decreases after some channels are labeled as bad. That means the $C$ in Eq.(2) becomes smaller than 79. As shown in Eq.(2) and Eq.(7), the smaller value of channel number may increases packet collision between difference bluetooth piconets and thus decrease the system aggregate throughput.

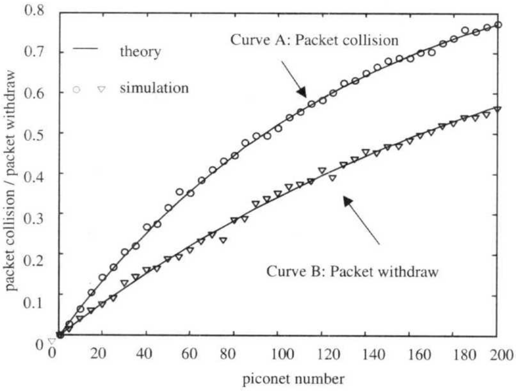

Fig. 4 packet collision probability and packet withdraw probability of full size DM1 data packet as a function of piconet number. The LBT window size is 50us.

Fig. 3 shows the packet collision and packet withdraw as a function of active piconet number. Curve A is the packet collision rate of full size DM1 packet *vs* DM1 packet, whereas curve B is the packet withdraw of DM1 packet. The solid line denoted the theoretical value obtained from Eq.(5) and Eq.(6), where the data packet size is 366us, $T$ is 1250us, and LBT window size is 50us. The simulation agrees very well with the theoretical values. The packet collision and packet withdraw increase with the increment of piconet number. However, it is clear that the packet withdraw increases much slowly than packet collision. This is because of the smaller size of LBT window compared with the data packet size. When there are 10 active piconets, the packet collision probability and packet withdraw probability is 0.064 and 0.032 respectively.

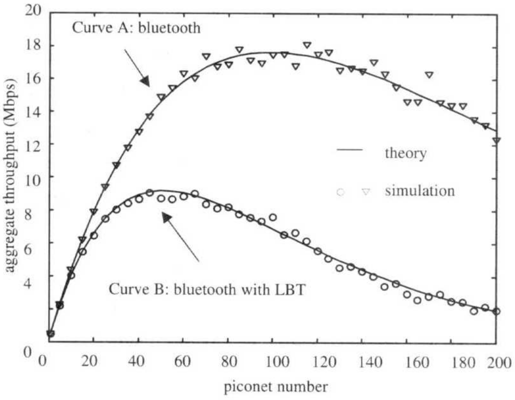

Fig. 5 Aggregate throughput as a function of active piconet number (DM5 packet). The LBT window size is 50us.

Both packet collision and packet withdraw incurs unsuccessful packet transmission from source to sink. As an example, Fig. 5 shows the full size DM5 packet aggregate throughput as a function of active piconet number before and after LBT. Curve A is the aggregate throughput of current bluetooth, and curve B is the bluetooth with LBT. The solid line denoted the theoretical value obtained from Eq.(7) and Eq.(8), where ñ is 477.8kbps, the data packet and ACK packet size is 2862us and 126us respectively [1]. The figure clearly shows, in current bluetooth, the maximal aggregate throughput does not improve when $N$ increases beyond 50. The maximal aggregate throughput is about 9.00Mb/s. However, for bluetooth with LBT, less packet withdraw makes the maximal throughput almost double. The LBT greatly increase the bluetooth aggregate throughput, especially when there are many active piconets. Again, the simulation agrees very well with the theoretical values. The above results are obtained based on the assumption that the bluetooth piconet can hear each other. If the assumption does not hold, the actual aggregate throughput may fall between Curves A and B depending on how many percent of the hidden devices.

Fig. 6 shows the simulation of aggregate throughput when there are both WLAN DS system and other bluetooth piconets with DM5 packet encapsulation. The four curves marked with bluetooth, LBT, AFH and LBT+AFH denote the aggregate throughput of bluetooth, bluetooth with only LBT, bluetooth with only AFH and bluetooth with the hybrid of LBT and AFH. In simulation, we assume that the channel monitor process has been finished and all the bad channels have been correctly labeled. For WLAN DS system, the data packet size is 1210us and the ACK packet size is 106us with a 10us interval between them. The next packet arrives 350us after the end of previous ACK [6]. For the concerned piconet, there are both frequency dynamic and frequency static interference. Due to the interference from WLAN DS, the maximal aggregate throughput of bluetooth decreases from 9.00Mb/s to 7.24Mb/s. Compared with the current bluetooth, the bluetooth with AFH provides larger throughput when piconet number is less than 40. When piconet number is beyond 40, it delivers smaller throughput than bluetooth. The reason is that AFH decreases frequency static interference at the expensive of increasing frequency dynamic interference. For example, in bluetooth, the probability of two packets shares the common channel is 1/79 [2]. However, after all WLAN DS channels have been labeled as bad, the probability of two packets uses the same channel becomes 1/57 [1,2]. With the increment of piconet number, the frequency dynamic interference becomes stronger than frequency static interference. The bluetooth with only LBT can only avoid the frequency dynamic interference and partial frequency static interference. When the piconet number is less than 20, it provides smaller throughput than the bluetooth with only AFH. This is due to the fact that frequency static interference is stronger in this case. For bluetooth with both LBT and AFH, the frequency dynamic interference is avoided by LBT, and the frequency static interference is avoided by AFH. Therefore, it delivers the maximal aggregate throughput. Compared with bluetooth, the maximal throughput almost doubles.

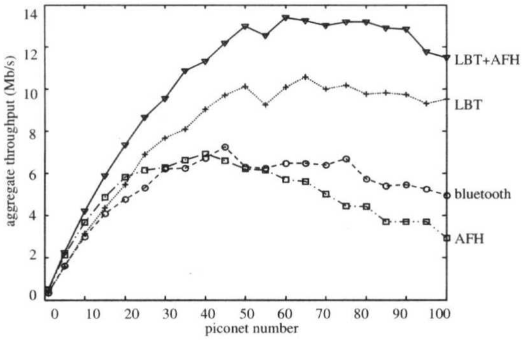

Fig. 6 Aggregate throughput with both WLAN DS and other piconets interferers (DM5 packet). The LBT window size is 50us.

## Ⅳ. IP traffic simulation

### 4.1 simulation model

A more realistic simulation is performed in this section. The considered experiment topology is shown is Fig. 7. It is similar to the experiment topology considered by Nada Golmie [8]. All the other bluetooth piconets are placed randomly with uniform distribution in the horizon platform, which can be considered as a rectangular room of size 10m*20m. The slaves are placed around the respective master. The slave device of bluetooth piconet we concerned locates at coordinates origin, while the master device can move along the horizon axis. The distance between slave and master changes the Signal-to-Noise Ratio at bluetooth sink. Each piconet contains a master and a slave. The bluetooth piconet performs frequency hopping over 79 carriers The WLAN DS system locates at the vertical axis. The WLAN DS contains an access point and a mobile device. The WLAN access point is fixed at (0,15), while the WLAN mobile is free to move along the vertical axis. The closer the WLAN mobile is, the stronger impacts of WLAN signal on bluetooth signal. The WLAN DS provides a maximum data rate 11Mb/s and bandwidth of the signal is 22MHz [1]. The configuration and system parameters are shown in Table 1.

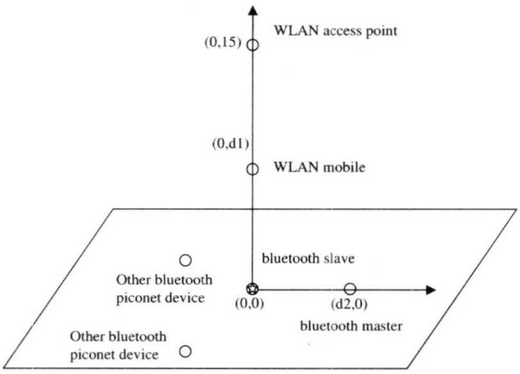

Fig. 7 Simulation experiment topology

Table 1. Simulation parameters

| Bluetooth parameters | | WLAN parameters | |
|---|---|---|---|
| Transmitted power | 1 mW | Transmitted powe | 25 mW |
| Slave coordinates | (0,0) m | AP coordinates | (0,15) m |
| Master coordinates | (d2,0) m | Mobile coordinates | (0,d1) m |
| DM5 packet interv | 29.16 ms | Packet interval | 2.52 ms |
| Other piconets | distance<br>U(1,10) m | Packet headers | 224 bits |
| Traffic load | 30 % | Traffic load | 30 % |
| | | Slot time | 20 us |
| | | SIFS | 10 us |
| | | DIFS | 50 us |
| | | CW_min, CW_ma | 31, 1023 |

We consider a LAN access application. This is typically a connection between a PC and an Access Point or between two PCs, and it allows for exchanging TCP/IP or UDP-like traffic. IP packets are generated according to the distribution presented in Table 2 [8]. The packet interval is exponentially distributed. We set the offered load to 30%of the channel capacity, which corresponds to mean packet inter arrival times of 29.16ms and 2.52ms for bluetooth and the 11Mbps WLAN DS systems, respectively. In bluetooth the packets are encapsulated with DM5 baseband packets after the corresponding PPP, RFCOMM, and L2CAP packet overheads totaling 17 bytes are added [6]. The average generated data rate is 248kbps for both directions in bluetooth piconet, and the average DM5 data packet size is 752 bits. For bluetooth piconet, the IP packet is from master to slave. For WLAN, the mobile is the generator of data, while the access point is the sink. Acknowledgement packet is returned from sink in both systems as response. Both the data and acknowledgement packet are considered to be susceptible to interference. The IP traffic is organized in session mode, each session is 20s. Furthermore, a packet may be transmitted several times due to ARQ scheme reacting on disturbances on the radio link.

Table 2. IP traffic: massage size distribution

| msg size (byte) | 64 | 128 | 256 | 512 | 1024 | 2048 |
|---|---|---|---|---|---|---|
| probability | 0.6 | 0.06 | 0.04 | 0.02 | 0.25 | 0.03 |

The channel model consists of geometry-based propagation model of the signal, as well as an additive white Gaussian noise (AWGN) model. The AWGN makes the BER to be $10^{-3}$ when the distance between bluetooth devices is 10m. The pass loss for indoor environment is given by

$$ploss = \begin{cases} 32.45 + 20\log(fd) & d < 8 \\ 58.3 + 33\log(d/8) & otherwise \end{cases} \tag{9}$$

where $f$ is the frequency in GHz, and $d$ is the distance in meters. This model is similar to the model used by Kamerman [9]. We assume unit gain for the transmitter and receiver antenna. We consider both co-channel and adjacent channel 1MHz interference. The attenuation of adjacent channel interference is 11dB, because the sensitivity difference of bluetooth device to co-channel interference and adjacent 1MHz interference is 11dB in bluetooth specification [2]. The adjacent 2MHz interference is not taken into consideration. The AWGN, co-channel and weighted adjacent channel interference are summed up as noise at receiver.

The GFSK modulation with modulation index of 0.5 is used in bluetooth system. While there are a number of possible receiver designs, we consider the non-coherent limiter-discriminator (LD) receiver. The performance of LD receiver is assumed to be perfect as in [16]. Due to the random time alignment and frequency hopping used in different piconet, the interference power may significantly vary during reception of a burst. Hence, for each received burst, an interference power profile and BER profile are obtained. From BER profile, the access code, header and payload failure probability of each burst is calculated. After bit error detection, error correction is performed according to the FEC algorithm of each part. The Hamming code (d=14) is applied to access code, a 1/3 rate FEC is applied to the packet header, while DM5 packet uses a 2/3 rate FEC to protect the payload. Any uncorrected error incurs packet failure.

We assume the LBT energy sense threshold is 70dBm. This is the reference sensitivity of bluetooth device [2]. If the signal power is above the threshold in LBT sense window, the channel is considered as a busy channel. Otherwise, it is free. The LBT window size is set to 50ìs. If a packet power from another piconet is below the LBT threshold in a LBT sense window, the source device in that piconet becomes a hidden device to the sink of packet after LBT window. Among the methods to monitor the channels, we select a simple one, only the packet loss of each channel is recorded [11]. The AFH first monitors the packet loss of each channel for 4s. In this period, the bluetooth transmits on regular hopping frequency. In monitor period, the bluetooth with only AFH is the current bluetooth; the packet loss may results from any packet collision. In monitor period, the bluetooth with both LBT and AFH is the bluetooth with only LBT; the packet loss may results from trial-edge packet collision bluetooth piconet and WLAN and the packet collision due to hidden devices . For bluetooth with both LBT and AFH, a threshold of one packet collision per second per channel is set. For bluetooth with only AFH, the threshold is set to two packet collisions per second per channel. Any channel whose packet loss is above the threshold is labeled as bad channel. Of course, not all the bad channels can be found in monitor period. After channel monitor, the piconet find the bad channels and use a new mapping sequence to avoid the bad channels. After the end of each traffic session, the bluetooth revert to the regular frequency hopping to re-evaluate the channels.

### 4.2 simulation results

All simulations are run for 10 sessions. The performance measurements are logged at the slave device of in the concerned piconet. The metrics include packet loss and link throughput. The packet loss the ratio of error data packets received at slave device. The link throughput is the average information bits correctly received at sink. Both the loss and withdraw of data packet and acknowledgement packet can fail the data packet transmission. The coordinate of WLAN mobile is fixed at (0,4) in simulation. The interference from WLAN to bluetooth increases when the WLAN mobile approaches the concerned bluetooth slave device.

Fig. 8 shows the packet loss for current bluetooth, bluetooth with only LBT, bluetooth with only AFH and bluetooth with the hybrid of LBT and AFH. The distance between slave and master is 2m. WLAN DS is an outstanding interferer to bluetooth. When there are 5 active piconets, among the 0.0854 packet loss, WLAN contributes 0.071 packet loss. With the increment of piconet, packet loss increases due to more packet collision between bluetooth piconets. For bluetooth with only LBT, the potential packet collisions between different bluetooth piconets and front-edge hits between bluetooth packets and WLAN packets that are above the LBT threshold are avoided. There are two sources of the remained packet loss. One is from the trail-edge collision between bluetooth packet and WLAN packet. Another is from the hidden terminals. Some piconets are hidden terminals to the sink in concerned piconet because of the factor of distance. They cannot sense the packet sent by packet source in concerned piconet. The packet loss declines with the increment of active piconet. The reason is that more packets are withdrawn because of LBT. With more piconets, there are more ongoing packets from other piconets. For bluetooth with only AFH, the packet loss decreases also compared with the bluetooth. However, the packet loss increases with the increment of piconet. The reason is that, after AFH, the number of good channel is less than whole channel number, and the packet collision between bluetooth piconets increases. For the bluetooth with both LBT and AFH, the packet loss is the least. If perfect LBT and AFH are performed, there will be no packet loss after the monitor period.

Fig. 9 shows the link throughput of piconet we concerned for bluetooth and bluetooth with LBT and AFH, where load denotes the offered traffics. The devices coordinates are the same as in Fig. 8. The link throughput decreases with the increment number of active piconet. When WLAN interferer and 5 piconets co-locate together, only 88.02% offered traffic can be transmitted. However, after the hybrid method, the link throughput decline compared with the current bluetooth. The reason is that we withdraw some packet collision that will not incur packet loss in LBT. For example, when the bluetooth master-slave distance is 2m and the distance between WLAN mobile interferer and the concerned slave device is 4m, if the packet collision occurs between them, the SNR at bluetooth slave device is about 13dB, which is high enough to make the correct receive in usually. However, in this case, LBT can sense packet from WLAN mobile and withdraw the packet transmission to avoid the potential packet collision. Fig. 10 shows the link throughput when bluetooth master-slave distance is 6m. The interferers topology distribution does not change. In this case, the bluetooth with LBT and AFH increases link throughput from 275.06kb/s to 300.84kb/s. If the maximal link throughput is wanted, the LBT window size and threshold must be optimized.

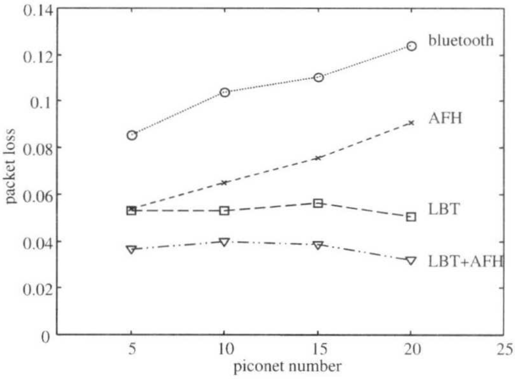

Fig. 8 Packet loss at bluetooth slave device. The master-slave distance is 2m. The coordinate of WLAN mobile is (0.4). The legends are the same as in Fig. 6.

## V. Discussion and Conclusions

The issue of coexistence is one of the more vexing problems that must be address. Bluetooth, WLAN and Microwave oven are likely to be the dominant interferers to bluetooth in coming year. This means that there are both frequency static interference and frequency dynamic interference.

Like adaptive fragment, the hybrid method of LBT and AFH is a non-collaborate coexistence method [11,12]. Adaptive fragmentation may increase system throughout if there is interference [11]. However, when there is no interference, fragmentation maybe reduces the link throughput. As shown in Eq.(7), with fixed size of access code and header, the shorter the packet size is, the smaller the value of ñ. This leads to the question: under what circumstance should fragmentation be enabled and what should the fragmentation level be set to. Only AFH is a static method and it may be useful only for frequency static interference, such as interferences from WLAN and Microwave [12]. In addition to that, the fragment and AFH cannot react to the interference in a real-time manner since they have to monitor the channel for a period of time [11,12]. Furthermore, the AFH may increase multi-piconets interference.

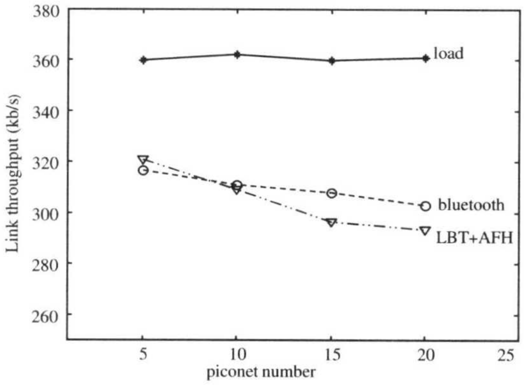

Fig. 9 Bluetooth link throughput when master-slave distance is 2m. The legends are the same as in Fig. 6.

Compared with the above methods, there are several benefits to use LBT in bluetooth. First, it is highly compatible with the current bluetooth specification. The standby time in current bluetooth is only for frequency synthesizer to tune to the next channel. It only needs a few extension of current bluetooth specification. Receiver Signal Strength Indicator (RSSI) function is only optional in bluetooth device supports power control [2] in The LBT supports the timing, the packet type and the MAC of the current bluetooth. Second, the hybrid method contains two complementary methods. The LBT is a dynamic scheme. Channel evaluation is performed only when the device wants to access it. With properly set threshold and receive filter, it can detect signal energy from WLAN, WPAN and other potential interferers. The AFH is a static scheme. It evaluates the channel condition and selects the good channels to use. It is especially useful when there are strong channel and frequency static interference. The third, it is power saving. Withdrawing packet transmission that tends to interfere others not only avoids packet collision, but also saves the power consuming of two devices. It decreases the potential packet retransmission.

The drawback of the hybrid method is that it is a non-collaborative method. Thus, the higher layer commands of system cannot be followed, say RTS/CTS in WLANs [1]. Another drawback is that, like any other wireless packet radio network with carrier sensing, the solution maybe suffers from what is called hidden terminal problem [1]. Because of centralized control in bluetooth piconet, the hidden terminal denotes the bluetooth device belonged to other piconets. Solutions to this problem are under further research.

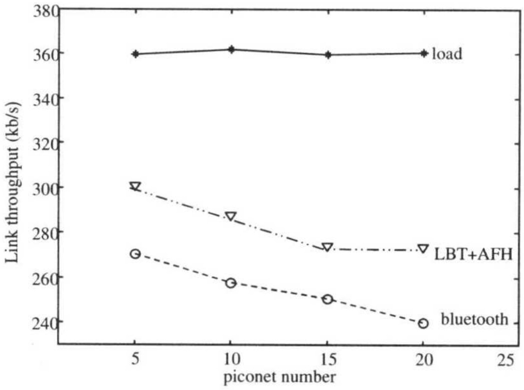

Fig. 10 Bluetooth link throughput when master-slave distance is 6m. The legends are the same as in Fig. 9.

In conclusion, we propose a novel hybrid method of Listen-Before-Talk and adaptive frequency hopping in bluetooth to solve the coexistence of WLANs and bluetooth. In bluetooth, before packet transmission in the beginning of next time slot, a check of the next channel is performed in turn around time of current time slot. If the channel is busy during sense window, the sender withdraws packet transmission and wait for next chance. The LBT senses transient availability of channel to combat the frequency dynamic interference. The AFH monitors long term availability of channel to combat the frequency static interference. We observe significant performance gains through packet collision analysis and detail realistic simulation. It turns out that the hybrid method can combat both the frequency dynamic and frequency static interference. The packet collision analysis shows it almost doubles the maximal system aggregate throughput. The realistic simulation shows it has the least packet loss.

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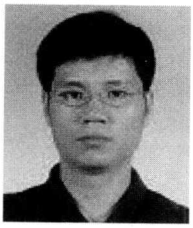

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