Interference Mediation for Coexistence of WLAN and ZigBee Networks

Byoung Hoon Jung, Jo Woon Chong, Chang Yong Jung, Su Min Kim, and Dan Keun Sung
School of EECS, Korea Advanced Institute of Science and Technology
373-1 Guseong-dong, Yuseong-gu, Daejeon 305-701, Korea
E-mail: bhjung@cnr.kaist.ac.kr, dksung@ee.kaist.ac.kr

Abstract— In emerging ubiquitous wireless environments, mobile devices can have multiple communication modules such as WLAN and ZigBee. Since IEEE802.15.4 ZigBee devices and IEEE802.11b WLAN devices share the same 2.4GHz ISM band, a ZigBee network operating in a low power environment can be severely interfered by overlapped WLAN networks with much larger bandwidth due to higher transmission power. To overcome this inter-system interference problem and guarantee the ZigBee communications, we propose an interference mediation scheme in an overlaid network environment of WLAN and ZigBee devices by using an interference mediator, and evaluate the performance of ZigBee and WLAN networks for three different resource allocation schemes in terms of throughput and channel occupancy time.

I. INTRODUCTION

Increasing user demands for diverse wireless services have brought wide deployment of various types of wireless networks in indoor environments. Three main network systems are IEEE 802.11 WLAN [1], IEEE 802.15.1 Bluetooth, and IEEE 802.15.4 ZigBee [2]. Since all these three communication systems share the same 2.4GHz ISM band, there exist inter-system interference.

The inter-system interference between WLAN and ZigBee networks has been studied. Sikora et al. [3] measured the performance of ZigBee devices with other communication devices. Kim et al. [4] proposed a coexistence scheme between ZigBee and WLAN, and Park et al. [5] measured the interference to WLAN from other devices. Kang et al. [6] proposed a coexistence scheme for ZigBee cluster-tree structures in order to avoid the inter-system interference of WLAN. Jung et al. [7] proposed a proactive and node-centric scheme to mediate the inter-system interference of WLAN and ZigBee devices. And Chong et al. [8] analyzed the ZigBee network throughput in the presence of WLAN interference.

The coexistence problem between WLAN and ZigBee devices, which considers different devices with different data rates, is similar to a multi-rate problem in WLAN. Fairness-based TDMA schemes have been used to solve the multi-rate problem in WLAN. Babu et al. [9] analyzed the performance of IEEE 802.11 under a multi-rate scenario and compared the time-based and throughput-based fairness schemes. Tan et al. [10] compared the time-based and throughput-based fairness schemes in IEEE 802.11 and showed that the time-based fairness scheme improves the performance in multi-rate WLANs. However, the transmission rate and MAC structures of the WLAN and ZigBee systems are different.

II. INTERFERENCE MEDIATION SCHEME FOR COLLOCATED ZIGBEE AND WLAN NETWORKS

To mediate this inter-system interference, we propose an interference mediation scheme in which an interference mediator(IM) coordinates the interference between WLAN and ZigBee networks using its internal WLAN and ZigBee modules. This IM plays an important role as a coordinator of mutual interference mediation between a ZigBee piconet and a WLAN BSS.

A. Structure of Proposed Interference Mediation Scheme

Fig. 1 shows a block diagram of the proposed interference mediation scheme which consists of a Channel Status Observation Part and an Interference Mediation Part.

1) Channel Status Observation Part: To observe the ZigBee channel status, the IM’s ZigBee module operates as a
piconet coordinator (PNC) in the ZigBee piconet and periodically gathers the frame error rate (FER) values from piconet’s ZigBee nodes. FER represents the ratio of the number of collided frames to the number of transmitted frames. \( FER_{TH} \) denotes the FER threshold.

If the FER value of a node is larger than \( FER_{TH} \), the node is considered to undergo severe interference from a WLAN network. Therefore, the IM can determine whether the piconet is under severe interference or not. Then, if there exists severe interference from a WLAN network, IM decides to operate the Interference Mediation Part.

2) Interference Mediation Part: In the Interference Mediation Part, the IM scans the existing WLAN AP channels using its internal WLAN device. Then, it searches for available ZigBee channels not overlapping with the existing WLAN networks. If there exists a new interference-free ZigBee channel, then the ZigBee piconet is reconfigured at the new ZigBee channel to avoid the existing inter-system interference.

If the inter-system interference from the WLAN network is too severe to communicate in the ZigBee channel, it is even difficult to change the ZigBee channel. If there is no interference-free channel or the inter-system interference is too severe to communicate, then the proposed scheme performs a fairness-based TDMA schemes to avoid the inter-system interference and guarantee ZigBee data communications.

Fig. 2 shows an example of one ZigBee and six WLAN networks in a collocated environment. WLAN APs communicate with WLAN stations using WLAN channels 1, 3, 6, 8, 11, and 13 in the 2.4GHz ISM band. In this environment, ZigBee devices which make an attempt to communicate in the collocated ZigBee network can not find a WLAN interference-free channel. Hence, it is hard for the ZigBee network to communicate without inter-system interference when there is no inter-system interference-free channel. Nowadays, there may exist many WLAN APs in indoor and outdoor environments which can cause the inter-system interference.

B. Proposed Fairness-based Coexistence Schemes in Interference Mediation Part

In this paper, we propose a fairness-based TDMA scheme as a solution of the severe inter-system interference problem between WLAN and ZigBee networks. In order to guarantee ZigBee data communications with a certain fairness, we propose a TDMA-based interference mediation scheme with the proposed superframe structure.

The main idea is to use the WLAN PCF duration to transmit ZigBee data and to use the inactive duration of ZigBee to transmit WLAN data. Using an AP-supporting Point Coordination Function (PCF), we can control the PCF duration and Contention Free Period (CFP) repetition interval.

During the WLAN Beacon period, an IM’s WLAN node reserves a PCF duration to transmit its ZigBee data while other WLAN nodes operate according to their Network Allocation Vector (NAV) and do not transmit data. In the ZigBee superframe structure, the IM’s ZigBee node, which operates as a PNC, controls its Contention Access period (CAP), Contention Free Period (CFP), and inactive interval to match the WLAN superframe structure to not to interfere, as shown in Fig. 3. In this paper, we assume that other WLAN nodes do not reserve the PCF duration to transmit.

Combining both the WLAN and ZigBee superframe structures, we can propose a superframe structure which is shown in Fig. 3.

To control the proposed superframe length, the IM receives the previous WLAN throughput and channel utilization information from AP by using the WLAN module, and gathers the previous ZigBee throughput and channel utilization information by using the ZigBee module to estimate the next superframe length. Then, the IM sends the estimated superframe length to the AP.

The main concern of the TDMA method is the ratio of time occupancy between WLAN and ZigBee networks in the proposed superframe structure. There are two existing schemes to select this ratio such as a time-based fair scheme, and a throughput-based fair scheme.

In this paper, we set the channel occupancy ratio of each system as follows:

\[
\text{Ratio}_{SYS} = \frac{aChOccupancy_{SYS}}{aSuperframeLength - aBeacon_{WL} - aBeacon_{ZB}},
\]

\( SY S \in \{WLAN, ZigBee\} \) (1)

1) Time-and Throughput-Based Fair Schemes: The time-based fair scheme here means that the same channel occupancy time is achieved for WLAN and ZigBee networks, while the throughput-based fair scheme is to achieve the same throughput for WLAN and ZigBee networks. The time-based fair scheme can guarantee that the ZigBee piconet uses exactly the same amount of channel occupancy time. The ZigBee data rate is extremely low, compared with that of the WLAN. In order to match the same amount of throughput, the throughput-based fair scheme sets a much higher ZigBee channel occupancy ratio, compared with that of WLAN. It results in an extremely low total aggregated throughput compared with the time-based fair scheme. Hence, the time-based fair scheme is a more...
appropriate solution than the throughput-based fair scheme, as shown in many previous studies.

To achieve the time- and throughput-based fairness, we can define the conventional fairness index \( f \) as \( f_{\text{time}} = \frac{\text{Ratio}_{WL}}{\text{Ratio}_{ZB}} \), using the channel occupancy ratio between WLAN and ZigBee networks, and \( f_{\text{throughput}} = \frac{S_{WL}}{S_{ZB}} \), where \( S_{WL} \) and \( S_{ZB} \) denote the throughput of WLAN and ZigBee system, respectively.

In order to achieve the throughput-based fair scheme, the IM should estimate the throughput of each system by using the previous traffic information of WLAN and ZigBee networks and based on this throughput estimation, the IM can determine the proper ratio.

However, this time-based fair scheme does not consider the difference between two systems. Moreover, when there is unbalance in channel activities between two systems, the time-based fair scheme wastes a certain amount of time resource in the less active system, and limits the performance of the more active system. In order to overcome this shortcoming, we propose the following per-data transmission time-based fair scheme:

2) Proposed per-Data Transmission Time-based Fair Scheme: To overcome the shortcoming of the previous time-based fair scheme, we propose a per-data transmission time-based fair scheme which considers the difference between WLAN and ZigBee systems and eliminates the waste of resources in the existing unbalanced channel activities between WLAN and ZigBee networks.

The main difference of the WLAN and ZigBee systems is the overhead induced by the different MAC/PHY standard. To transmit the same amount of data, WLAN and ZigBee require different overhead such as MAC/PHY frame header, RTS/CTS signal, ACK, and back off time. The proposed scheme first considers the difference of the system overhead and achieves the actual data transmission time to be identical.

The average successful and collided transmission time of one frame in the WLAN system is, respectively, as follows:

\[
T_{s,WL} = \text{Header}_{WL} + L_{WL} + \text{SIFS}_{WL} + \delta_{WL} + \text{ACK}_{WL} + \delta_{WL} + \text{DIFS}_{WL} + t_{\alpha,WL} \\
T_{c,WL} = \text{Header}_{WL} + L_{WL} + \text{SIFS}_{WL} + \delta_{WL} + \text{ACK}_{Timeout,WL} + t_{\alpha,WL},
\]

where the parameters are listed in Table I.

The average successful and collided transmission time of one frame in the ZigBee system is, respectively, as follows:

\[
T_{s,ZB} = 2\text{CCA}_{ZB} + \text{Header}_{ZB} + L_{ZB} + t_{TA,ZB} + \text{ACK}_{ZB} + t_{\alpha,ZB} \\
T_{c,ZB} = 2\text{CCA}_{ZB} + \text{Header}_{ZB} + L_{ZB} + t_{TA,ZB} + \text{ACK}_{Timeout,WL} + t_{\alpha,ZB},
\]

where the parameters are listed in Table I.

If one system fully utilizes the given time resource and the other does not, the proposed scheme allocates the unused time resource of the less active system to the system with higher utilization. If both systems have lower utilization or higher utilization, the proposed scheme shares the same data transmission time. Fig. 4 shows an example when the WLAN network fully utilizes the give time resource and the overlapped ZigBee network does not.

To achieve the proposed per-data transmission time-based fairness, we can set the fairness index \( f \) using each systems ratio as described in Eq. (4), where \( W_{\text{WasteWL}} \) and \( W_{\text{WasteZB}} \) denote the unused time of WLAN and ZigBee, respectively. These values can be obtained from the difference between the channel occupation time of the time-fair scheme and the estimated required time to serve the current offered load.

If both WLAN and ZigBee fully utilize the time or are less active,

\[
f_{\text{proposed}} = \alpha \times \frac{\text{Ratio}_{WL}}{\text{Ratio}_{ZB}}, \quad \alpha = \frac{O_{WL}}{O_{ZB}}
\]

Else

\[
f_{\text{proposed}} = \alpha \times \frac{\text{Ratio}_{WL}}{\text{Ratio}_{ZB}}, \quad \alpha = \frac{O_{WL}}{O_{ZB}} \frac{\text{Ratio}_{ZB} - W_{\text{WasteZB}} + W_{\text{WasteWL}}}{\text{Ratio}_{ZB} + W_{\text{WasteZB}} - W_{\text{WasteWL}}} \tag{4}
\]

where \( O_{WL} = T_{s,WL}/L_{WL} \), and \( O_{ZB} = T_{s,ZB}/L_{ZB} \). The terms \( O_{WL} \) and \( O_{ZB} \) here denote the total required time per unit data transmission of the WLAN and ZigBee systems, respectively. The weight \( \alpha \) considers the difference between WLAN and ZigBee systems, and achieves the proposed per-data transmission time fairness.

III. SIMULATION AND ANALYSIS RESULTS

We assume that the WLAN and ZigBee channels are overlaid and there is no inter-system interference-free channel in the ZigBee network. The WLAN and ZigBee devices frames arrive according to a Poisson process with input rates \( \lambda_{WL} \) and \( \lambda_{ZB} \), respectively. The WLAN devices in the IM can receive the WLAN network information from AP and can decide WLAN AP’s beacon frame length using the proposed scheme. Under these assumptions, IM can estimate and control both WLAN and ZigBee networks. The proposed fairness-based TDMA superframe length of each system is set to 61.6msec.

The performance of ZigBee and WLAN communications is estimated in terms of the throughput and channel occupancy time for varying the offered load. The offered load is calculated as follows:

\[
\text{OfferedLoad} = \lambda_{SYS} \times L_{\text{Frame,SYS}} \times N_{SYS}/R_{SYS},
\]

\[
SYS \in \{\text{WLAN, ZigBee}\}, \tag{5}
\]
TABLE I
WLAN AND ZIGBEE NETWORK PARAMETER

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{WL}$</td>
<td>Frame length of WLAN</td>
<td>500 bytes</td>
</tr>
<tr>
<td>$R_{WL}$</td>
<td>Data transmission rate of WLAN</td>
<td>113 Mbps</td>
</tr>
<tr>
<td>$CW_{min,WL}$</td>
<td>Minimum CW size of WLAN</td>
<td>31</td>
</tr>
<tr>
<td>$\delta_{WL}$</td>
<td>Unit slot time of WLAN</td>
<td>20 μsec</td>
</tr>
<tr>
<td>$Header_{WL}$</td>
<td>Header tx time of WLAN</td>
<td>210 μsec</td>
</tr>
<tr>
<td>$SIFS_{WL}$</td>
<td>SIFS time of WLAN</td>
<td>10 μsec</td>
</tr>
<tr>
<td>$\delta_{WL}$</td>
<td>Propagation Time of WLAN</td>
<td>2 μsec</td>
</tr>
<tr>
<td>$ACK_{WL}$</td>
<td>ACK tx time of WLAN</td>
<td>304 μsec</td>
</tr>
<tr>
<td>$DIFS_{WL}$</td>
<td>DIFS time of WLAN</td>
<td>50 μsec</td>
</tr>
<tr>
<td>$t_o,WL$</td>
<td>Average backoff time of WLAN</td>
<td>1500 μsec</td>
</tr>
<tr>
<td>$N_{WL}$</td>
<td>Number of active WLAN nodes</td>
<td>10</td>
</tr>
<tr>
<td>$L_{ZB}$</td>
<td>Frame length of ZigBee</td>
<td>105 bytes</td>
</tr>
<tr>
<td>$R_{ZB}$</td>
<td>Data transmission rate of ZigBee</td>
<td>250 kbps</td>
</tr>
<tr>
<td>$CW_{min,ZB}$</td>
<td>Minimum CW size of ZigBee</td>
<td>7</td>
</tr>
<tr>
<td>$\delta_{ZB}$</td>
<td>Unit slot time of ZigBee</td>
<td>320 μsec</td>
</tr>
<tr>
<td>$CCA_{ZB}$</td>
<td>CCA time of ZigBee</td>
<td>320 μsec</td>
</tr>
<tr>
<td>$Header_{ZB}$</td>
<td>Header tx time of ZigBee</td>
<td>192 μsec</td>
</tr>
<tr>
<td>$ACK_{ZB}$</td>
<td>ACK tx time of ZigBee</td>
<td>352 μsec</td>
</tr>
<tr>
<td>$t_o,ZB$</td>
<td>Average backoff time of ZigBee</td>
<td>1120 μsec</td>
</tr>
<tr>
<td>$N_{ZB}$</td>
<td>Number of active ZigBee nodes</td>
<td>10</td>
</tr>
</tbody>
</table>

When we use the time-based fair scheme, the throughput of the WLAN is saturated at a certain point and it grows linearly before the saturation point.

In the time-based fair scheme, both systems have the same channel occupancy. The saturation point of each network is different. If the throughput of one system is saturated and the other is not, because of the time-based fair scheme, there is a waste of time.

In the throughput-based fair scheme, the throughput of WLAN is bounded to that of the ZigBee because the throughput of ZigBee is much smaller than that of the WLAN. And when the throughput of WLAN is smaller than that of the ZigBee, the proposed scheme lowers the channel occupancy time of ZigBee to match the throughput. The throughput of ZigBee is almost the same when the offered load of WLAN is bigger than 0.3. It implies that the throughput of ZigBee is smaller than that of the WLAN in this case. The channel occupancy time of ZigBee is 0.97 and that of the WLAN is 0.03 in the throughput-based fair scheme. Until the throughput of both systems is saturated, the channel occupancy time varies. And the channel occupancy time of the ZigBee is extremely high, compared with that of the WLAN. This is the main shortcoming of the throughput-based fair scheme. And this resource allocation is not fair to the WLAN network and it is a waste of the time and channel resources.

The aggregated throughput of the time-based fair scheme is higher than that of the throughput-based fair scheme regardless of whether the system throughputs are saturated or not, as shown in Fig. 6. Thus, we can select the time-based fair scheme as a better scheme than the throughput-based fair scheme.

C. Proposed per-Data Transmission Time-based Fair Scheme

Fig. 7 shows the throughput of the WLAN and ZigBee networks for varying offered loads of ZigBee in the proposed per-data transmission time-based fair scheme. We eliminate the system difference by achieving per-data transmission time...
fairness, and give more appropriate channel utilization between WLAN and ZigBee systems, compared with that of the time-fair scheme. When the offered load of WLAN is set to more than 1, the WLAN fully utilizes the given time. Since the channel occupancy time varies, the throughput of the fully utilized system increases even if its offered load is fixed. If the throughput of one system is fully utilized in the given time and the other is not, then the proposed scheme allocates the anticipated remaining time of the less active system to the other. In this case, we can utilize the channel and time resources more efficiently than the original time-based fair scheme. Fig. 7 shows that the aggregated throughput of the proposed scheme is bigger than the original time-based fair scheme. When the offered load of WLAN is set to more than 1, the WLAN fully utilizes the given time. Since the time-based fair scheme has a much larger aggregated throughput, we choose the time-based fair scheme as a better solution. However, the time-based fair scheme does not consider the system difference of the WLAN and ZigBee. Moreover, there exists a waste if one system fully utilizes the time resource and the other does not. To overcome this shortcoming, we proposed a per-data transmission time-based fair scheme which considers the difference of each system and eliminates the shortcoming of the time-based fair scheme and yields much more aggregated throughput.

ACKNOWLEDGMENT

"This research was supported by the Ministry of Knowledge Economy, Korea, under the ITRC support program supervised by the IITA” (IITA-2008-C1090-0801-0037)

REFERENCES


