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Research Article

An Adaptive WLAN Interference Mitigation Scheme for ZigBee Sensor Networks

Jo Woon Chong,[1] Chae Ho Cho,[2] Ho Young Hwang,[3] and Dan Keun Sung[4]

[1]*Department of Biomedical Engineering, Worcester Polytechnic Institute, 100 Institute Road, Worcester, MA 01609, USA*
[2]*Department of Biomedical Engineering, University of Connecticut, Storrs, CT 06269, USA*
[3]*Department of Computer Engineering, Kwangwoon University, 20 Gwangun-ro, Nowon-gu, Seoul 139-701, Republic of Korea*
[4]*Department of Electrical Engineering, Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Yuseong-gu, Daejeon 305-338, Republic of Korea*

Correspondence should be addressed to Dan Keun Sung; dksung@ee.kaist.ac.kr

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We propose an adaptive interference avoidance scheme that enhances the performance of ZigBee networks by adapting ZigBees' transmissions to measured wireless local area network (WLAN) interference. Our proposed algorithm is based on a stochastic analysis of ZigBee operation that is interfered with by WLAN transmission, given ZigBee and WLAN channels are overlaid in the industrial, scientific, and medical (ISM) band. We assume that WLAN devices have higher transmission power than ZigBee devices. Then, the high transmission power of WLAN devices causes the capture effect when WLAN and ZigBee transmit simultaneously. On the other hand, ZigBee performs backoff during clear channel assessment (CCA) operation if the WLAN is transmitting its frames on the channel. We adopt a widely used WLAN queueing/transmission model that is based on a Markov chain concept. We model a ZigBee device's operation using the Markov chain that includes WLAN interference statistically derived from the WLAN queueing/transmission model. Our proposed algorithm is evaluated in a simulated ZigBee network in the presence of varying WLAN interference. Numerical results show that our WLAN interference mitigation scheme finds the ZigBee control parameters, among a candidate set, which enhances ZigBee network performance compared to the conventional ZigBee operation.

1. Introduction

Wireless local area network (WLAN), Bluetooth, and ZigBee technologies have been adopted in various types of devices as user demands for wireless services in local or personal areas increase. For example, WLAN access points (APs) have been widely deployed in indoor or outdoor environments, and tablets or laptops use WLAN technology for an internet connection. Bluetooth technology has been used in wireless headsets for audio devices, hands-free sets for mobile phones, and wireless keyboards and mouses for personal computers. ZigBee technology has gained attention from many companies since it consumes relatively less energy than other wireless technologies and can be implemented at low cost [1]. However, WLAN, Bluetooth, and ZigBee devices all operate on the 2.4 GHz industrial, scientific, and medical (ISM) band; hence if they coexist, they interfere with one another [2–6].

ZigBees are required to conform to the physical layer (PHY) and medium access control (MAC) techniques of IEEE 802.15.4, which is standardized for low-rate wireless personal area networks (WPANs). IEEE 802.15.4 defines operations in the 2.4 GHz (worldwide), 868 MHz (Europe), and 915 MHz (Americas and Australia) ISM bands [7–10]. The maximum data rate is 250 kbps per channel and the transmission distance is around 10–20 m in indoor environment. The ZigBee protocol supports both beacon-enabled and beaconless modes. In the beacon-enabled mode [11], a coordinator synchronizes nodes by sending beacons. A superframe is limited by two consecutive beacons and is composed of active and inactive periods. The active period can be divided into a contention access period (CAP) and a contention-free period (CFP). Slotted carrier sense multiple access/collision avoidance (CSMA/CA) and time division multiple access (TDMA) are channel access modes in CAP

and CFP, respectively [12–16]. In the beaconless mode, unslotted CSMA/CA is a channel access mode. During the inactive period in a superframe, all the nodes go into sleep.

Slotted and unslotted CSMA/CA mechanisms perform operations of initialization, backoff, clear channel assessment (CCA), starting the transmission, and acknowledgement (optional) [17, 18]. Initialization is a procedure of setting a node's local backoff exponent variable to an initial value whenever a frame is successfully transmitted by the node. The backoff is a procedure of keeping the node silent before trying to assess the channel medium. This backoff lowers a frame collision probability by randomizing its channel assessment time. After the backoff, the node performs CCA. If the channel is assessed to be busy, the node performs backoff again after doubling backoff window size. This is to reduce a frame collision probability [19]. If the channel is assessed to be free during two CCAs, on the contrary, it starts its transmission. If the sending node requires an acknowledgement, the receiving node transmits an acknowledgement when the transmission is successful. Otherwise, the sending node regards it as transmission failure and retransmits its frame.

WLAN and Bluetooth devices have higher transmission powers compared to ZigBee devices by a factor of approximately ten to thousand times [17, 20]. In particular, the operating bandwidth of WLAN devices is wider than that of ZigBee devices; hence, if WLAN and ZigBee devices coexist and their operating bands are overlaid, the performance of ZigBee networks can be severely degraded by WLAN networks. On the other hand, WLAN transmission can be merely interfered with by ZigBees' transmissions. In this paper, we evaluate the performance of ZigBee networks interfered with by WLAN networks and propose an adaptive WLAN interference mitigation scheme for ZigBee networks. Our algorithm is based on the analysis and design of ZigBee's medium access control (MAC) operation when the ZigBees are interfered with by WLAN transmissions. Our heterogeneous interference analysis is based on a Markov chain concept, adopting WLAN and ZigBee operation models from IEEE 802.11 and IEEE 802.15.4 specifications, respectively [20, 21]. The proposed interference avoidance algorithm adapts ZigBees' transmissions to the measured WLAN interference, in order to maximize ZigBee networks' performance. Our proposed unified analysis and design of ZigBee networks have wide applicability in that they can be utilized in predicting and enhancing the performance of random access MAC-based networks interfered with by other heterogeneous random access MAC-based networks or virtual slot-based networks.

The rest of this paper is organized as follows. We describe related work in Section 2. ZigBee and WLAN protocols are explained in Section 3. The coexisting ZigBee and WLAN network environment that we consider is presented. In Section 4, the ZigBee operation interfered with by WLAN transmissions is modeled based on a stochastic analysis with a Markov chain concept. Interference avoidance algorithms for ZigBee networks interfered with by WLAN are proposed in Section 5. Section 6 describes performance measures and gives analytical and simulation results. Finally, Section 7 concludes this paper.

2. Related Work

The mutual interference problems among WLAN, Bluetooth, and ZigBee networks in the 2.4 GHz ISM band have been investigated in [22–30]. In [22, 23], the ZigBee frame error rate (FER) was measured when ZigBee devices coexist with WLANs and microwave ovens. Cochannel interference among ZigBee, Bluetooth, WLAN, and microwave ovens was evaluated in terms of frame loss of each system in [24]. The ZigBee packet error rate (PER) was evaluated through simulation when WLAN transmissions interfere with ZigBees' operation [25]. The opposite interference analysis, that is, ZigBee devices' interference on WLAN, was performed in [26, 27], which suggests that the effect of ZigBee transmissions on the WLAN is relatively insignificant compared to the reverse. In physical (PHY) layer, the performance of IEEE 802.15.4 ZigBee in the presence of IEEE WLAN (802.11b) and/or Bluetooth interference was analyzed in [28]. Here, they obtained the bit error rate (BER) performance under a varying signal-to-interference-plus noise ratio (SINR). In [29], the coexistence of ZigBee and WLAN in smart grid environments was investigated by measuring ZigBees' PER when ZigBee coexists with WLAN. In these studies, the interference is observed mainly in the PHY layer, and the WLAN interference to ZigBee is observed to be relatively severer than the reverse. This is due to the higher transmission power of WLAN devices compared to that of ZigBee devices. To standardize a coexistence algorithm for Bluetooth networks interfered with by WLAN networks, IEEE 802.15.2 working group (WG) has investigated the interference between WLAN and Bluetooth networks [30]. However, it focused on not ZigBee but Bluetooth.

The previous studies related to interference analysis mainly dealt with the operation among homogeneous ZigBee devices [31–33] or WLAN devices [34–38] without considering the heterogeneous interaction between ZigBee and WLAN. There exist analysis studies on the ZigBees' MAC operation interfered with by WLAN, but the WLAN interference is modeled by unrealistic the M/G/1 model [39, 40]. We model a WLAN queueing/transmission model reflecting a realistic WLAN MAC operation and transmission procedure, that is, CSMA/CA [34, 41]. The ZigBee network performance interfered with by WLAN interference is modeled by a Markov chain concept with WLAN interference parameterized in the Markov chain model. The proposed interference avoidance algorithm maximizes ZigBee networks' performance, for example, throughput, delay, and energy consumption, by controlling ZigBees' MAC parameters as well as ZigBee's frame size based on this analysis results.

The previous studies of the interference between WLAN and ZigBee [2–6] suggested that the way of mitigating the interference between WLAN and ZigBee is for ZigBee devices to avoid WLAN operating channels when ZigBee devices use their channels. Here, static and dynamic channel assignment methods are considered. The static assignment can be ineffective when the number of WLAN APs increases

or nodes are mobile [3] while the dynamic assignment methods can address these problems by avoiding nearby WLAN channels [42, 43]. However, these dynamic methods also become inefficient when there exists little WLAN traffic [2, 44]. The interference problems have also been investigated in the aspects of wireless sensor placement or sensor network topology [45–47]. In [45], the signal strength within an area is measured for IEEE 802.11a/b/g/n while a method for determining the optimal sensor placement based on [45] was proposed, which led to a reduction in the number of sensors to cover the area in [46]. A proactive method mediating the interference of WLAN and ZigBee devices is proposed in [48], and another in [49], with the concept of fairness additionally considered. A coexistence algorithm enabling ZigBee links to exploit WLAN white is proposed in [50]. An error detection and recovery method using partial packets are proposed to enhance link reliability in [51].

3. System Model

3.1. ZigBee and WLAN Networks. A ZigBee network can be configured in star or peer-to-peer topology. In the star topology, one ZigBee device, which is a full-function device (FFD), becomes a personal area network coordinator (PNC). Other ZigBee devices, which can be either reduced-function devices (RFDs) or FFDs, communicate with each other under the control of PNC. ZigBees start communication after associating themselves with PNC. The peer-to-peer topology is different from the star topology in the fact that devices can directly communicate with each other without PNC's relaying role. A ZigBee has 16 channels in the 2.4 GHz ISM band. The operation channels of ZigBee devices in the same network are configured by the same channel. For MAC protocol, ZigBees can use either CSMA/CA (mandatory) or TDMA (optional) [17]. When ZigBee devices gain channel access, they transmit data using a direct sequence spread spectrum (DSSS) physical layer technique.

A WLAN network consists of basic service sets (BSSs), where WLAN devices communicate with each other under the control of access points (AP). Both IEEE 802.11b and IEEE 802.11g PHYs have thirteen channels, respectively, each of which has 22 MHz bandwidth [52, 53]. The WLAN devices within the same BSS contend for channel access to transmit their frames. IEEE 802.11 incorporates CSMA/CA and TDMA services in the MAC protocol. IEEE 802.11b and IEEE 802.11 g use DSSS and orthogonal frequency division multiplexing (OFDM), respectively, in transmitting data.

Figure 1 illustrates coexisting WLAN and ZigBee networks. For PHY layer techniques, IEEE 802.11b and IEEE 802.11g for WLAN and IEEE 802.15.4 for ZigBee operating in the 2.4 GHz ISM band are considered. Hence, if their operating bands are overlaid, the WLAN operation band is considered to completely or significantly overlay ZigBee operation band [17, 52–54]. For MAC layer techniques, mandatory slotted CSMA/CA mechanisms of WLAN and ZigBee are considered. We mainly focus on the operation of MAC protocols. Figures 2 and 3 illustrate the CSMA/CA mechanisms of ZigBee and WLAN devices, respectively. The unit slot lengths of ZigBee, IEEE 802.11b, and IEEE 802.11g are

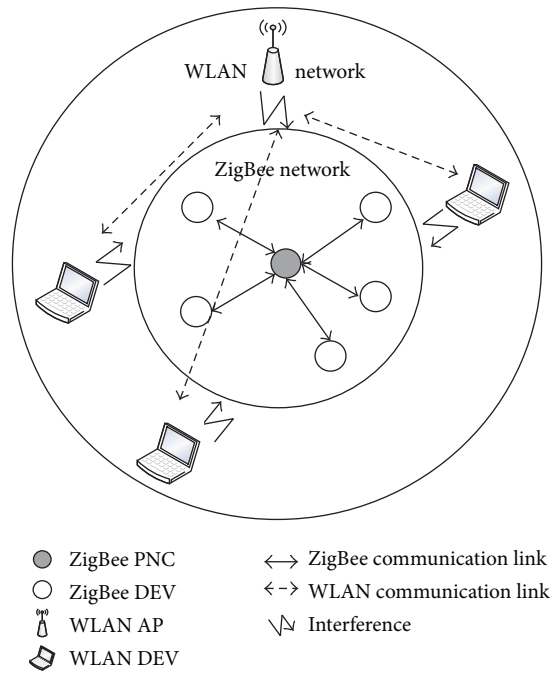


Figure 1: ZigBee and WLAN networks with mutual interference.

320 μs, 20 μs, and 9 μs, respectively [17, 52, 53]. ZigBee and WLAN devices decrease their backoff counter values if the shared channel is not busy. However, ZigBee device senses its shared channel twice only after the backoff counter expires (when the backoff counter value reaches 0) while WLAN always senses its shared channel; hence, a ZigBee does not freeze its backoff counter during other ZigBees' transmissions unless its backoff counter expires while WLAN freezes it during other WLANs' transmissions. Also, ZigBee increases its backoff stage and randomly selects its backoff counter value when the channel is busy or its transmitted frame is collided while WLAN does the same procedure only when its transmitted frame is collided.

3.2. Coexistence of ZigBee and WLAN: Medium Access Mechanisms. Figure 4 shows three possible cases of simultaneous channel access from ZigBee and WLAN devices when they coexist, as shown in Figure 1. In *case 1*, when WLAN starts its transmission earlier, it ignores ZigBee transmission and keeps its transmission procedure. Here, the WLAN transmission includes both successful and collided WLAN transmissions. In *case 2*, on the other hand, when ZigBee starts its transmission earlier, it detects the WLAN transmission during *CCA* periods and defers its transmissions. In *case 3*, when WLAN and ZigBee start their transmissions at the same time, the WLAN transmission interferes with the ZigBee transmission while the ZigBee transmission does not. This is due to the difference between transmission powers of WLAN and ZigBee. Although there exists a skew between ZigBee and WLAN transmissions in *case 3*, the same analysis can be given since one ZigBee CCA duration (128 μs) partially occupies the ZigBee unit slot (320 μs). We statistically parametrize WLAN interference in Section 4 in the process of modeling the operation of ZigBees.

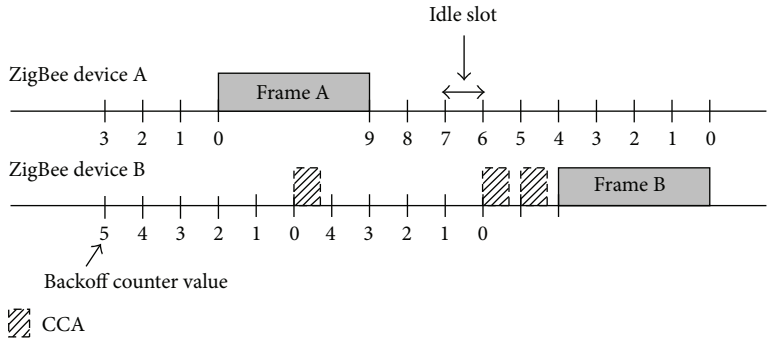


Figure 2: CSMA/CA mechanism of ZigBee devices.

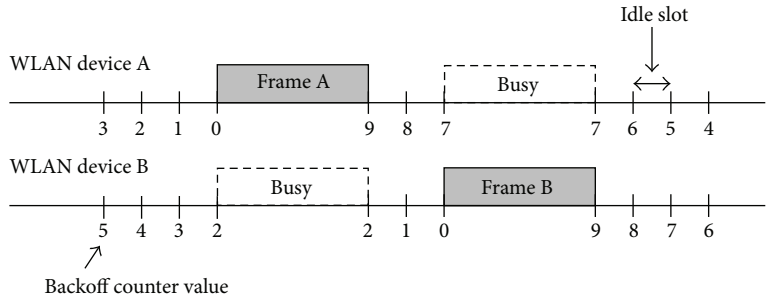


Figure 3: CSMA/CA mechanism of WLAN devices.

4. ZigBee Operation Model Interfered with by WLAN Transmission

4.1. ZigBee Operation: Markov Chain. The operation of a ZigBee device is basically modeled by a Markov chain model as shown in Figure 5 [32]. A *node* in the Markov chain represents a *state* $s_{i,j}$, where i and j are backoff stage and backoff counter values, respectively. A *directed arrow* between two nodes indicates the direction of state transition, and the number on the directed arrow indicates the *transition probability* between states [55, 56]. The states can be classified into *backoff states* or *nonbackoff states* depending on the values i and j. The backoff state is defined as $\{s_{i,j} \mid i \in [0,m], j \in [0, CW_i - 1]\}$, where CW_i is the contention window size at backoff stage i and m is the maximum backoff stage value. The nonbackoff states are the remaining states, which cannot be reached by the backoff procedure but can be by the CCA procedure.

A ZigBee device initializes its operation at a randomly selected backoff state of the first row, that is, $\{s_{i,j} \mid i = 0, j \in [0, CW_0 - 1]\}$. The ZigBee decreases its backoff counter by one ($j \rightarrow j - 1$) per each backoff unit slot σ until the counter reaches 0 ($j = 0$). When j reaches 0, the ZigBee performs channel sensing, called CCA, to check channel occupancy. When the first CCA outcome informs that the channel is *busy*, the ZigBee increments its backoff stage by one ($i \rightarrow i + 1$) and randomly selects j from $[0, CW_{i+1} - 1]$. If the channel is sensed as *idle*, the second CCA is performed. If the second CCA determines the channel is busy, the Zigbee does the same procedure as the busy case of the first CCA operation. Otherwise, the device sends its frame to its corresponding receiver.

The transition probabilities between states are given by

$$
\begin{aligned}
&\mathbb{P}\left\{s_{i,j} \mid s_{i,j+1}\right\} = 1, \quad i \in (0,m), \ j \in \left(0, CW_i - 2\right), \\
&\mathbb{P}\left\{s_{i,-1} \mid s_{i,0}\right\} = 1 - \rho, \quad i \in (0,m), \\
&\mathbb{P}\left\{s_{i,j} \mid s_{i-1,0}\right\} = \frac{\rho}{CW_i}, \\
&\qquad\qquad i \in (1,m), \ j \in \left(0, CW_i - 1\right), \\
&\mathbb{P}\left\{s_{i,j} \mid s_{i-1,-1}\right\} = \frac{\zeta}{CW_i}, \\
&\qquad\qquad i \in (1,m), \ j \in \left(0, CW_i - 1\right), \\
&\mathbb{P}\left\{s_{0,j} \mid s_{i,-1}\right\} = \frac{(1-\zeta)}{CW_0}, \\
&\qquad\qquad i \in (1,m-1), \ j \in \left(0, CW_0 - 1\right), \\
&\mathbb{P}\left\{s_{0,j} \mid s_{m,0}\right\} = \frac{\rho}{CW_0}, \quad j \in \left(0, CW_0 - 1\right), \\
&\mathbb{P}\left\{s_{0,j} \mid s_{m,-1}\right\} = \frac{1}{CW_0}, \quad j \in \left(0, CW_0 - 1\right),
\end{aligned}
\tag{1}
$$

where ρ and ζ are the 1st and 2nd CCA busy probabilities, respectively. The WLAN interference is reflected in ρ and ζ in this Markov chain. Since the parameters except ρ and

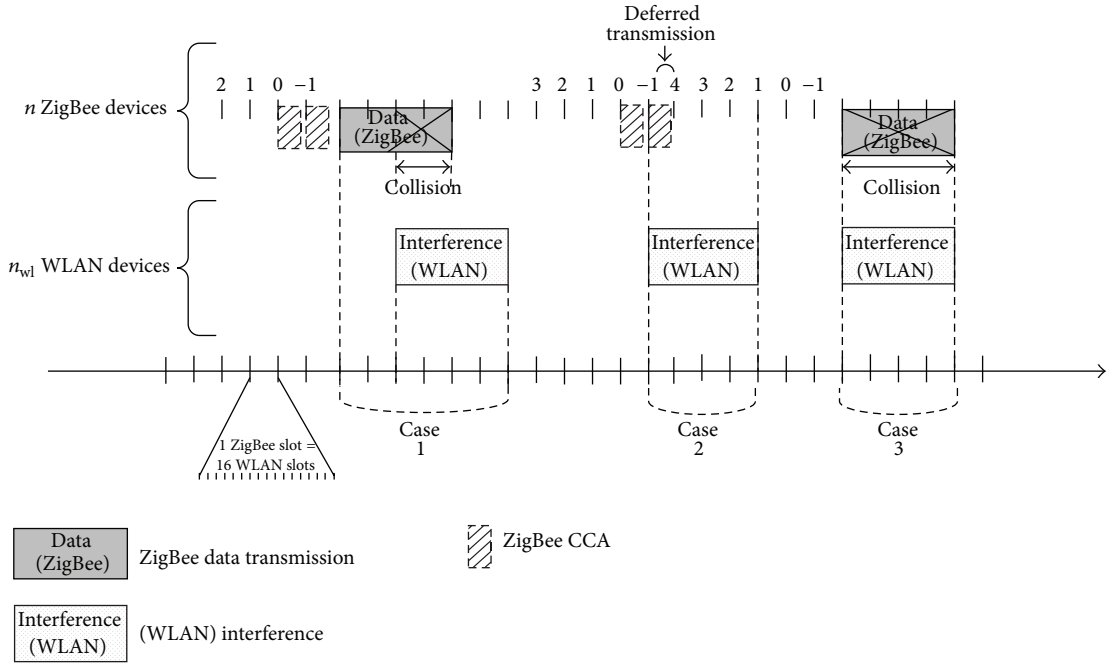


Figure 4: CCA operation of ZigBee devices interfered with by WLAN.

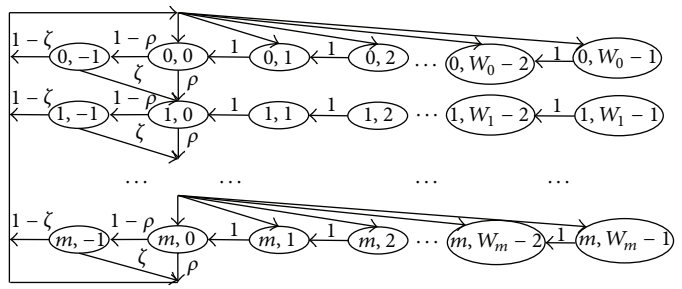


Figure 5: ZigBee operation model using a Markov chain concept.

ζ are given system parameters [17], ρ and ζ need to be characterized to complete an analysis model for the ZigBee operation in the presence of WLAN interference.

To obtain ρ and ζ, we tag one ZigBee which senses the shared channel even when $j > 0$ but with turning off the connection between the CCA and backoff counter elements[1]. The tagged ZigBee operates the same in the CCA and transmission modes as other normal ZigBees. As a result, ρ and ζ are equal to the first and second channel busy probabilities of this tagged ZigBee, respectively. Figure 6 shows an operation example of coexisting ZigBee and WLAN devices with a tagged ZigBee. The channel busy status is detected by the tagged ZigBee in three types of intervals: (i) only WLAN devices transmit frames (Intervals 1 and 7), (ii) only other ZigBee devices transmit frames (Intervals 2, 3, and 5), or (iii) WLAN and ZigBee devices simultaneously transmit frames (Interval 6). Hence, ρ is written by

$$\rho = \rho_{\text{wl}} + \rho_{\text{zb}} - \rho_{\text{wl+zb}}, \tag{2}$$

where ρ_{wl}, ρ_{zb}, and $\rho_{\text{wl+zb}}$ denote the tagged ZigBee's first channel busy probabilities caused by WLAN devices, other ZigBee devices, and both of WLAN and ZigBee devices, respectively.

Similarly, the second CCA busy probability ζ is written by

$$\zeta = \zeta_{\text{wl}} + \zeta_{\text{zb}} - \zeta_{\text{wl+zb}}, \tag{3}$$

where ζ_{wl}, ζ_{zb}, and $\zeta_{\text{wl+zb}}$ denote the tagged ZigBee's second channel busy probabilities caused by WLAN devices, other ZigBee devices, and both of WLAN and ZigBee devices, respectively.

4.2. WLAN Interference Affecting ZigBee Clear Channel Assessment Operations: ρ and ζ. To derive ρ_{wl}, WLAN transmissions on the shared channel need to be analyzed in the viewpoint of the tagged ZigBee. Let Ψ_{wl}, σ_{wl}, and T_{cca} be the number of WLAN consecutive idle slots, one WLAN backoff unit duration in seconds, and one ZigBee CCA duration in seconds, respectively. Specifically, Ψ_{wl} is a random variable, which can be counted in a network viewpoint, determined by WLAN transmission characteristics including transmission probability, success probability, collision probability, frame

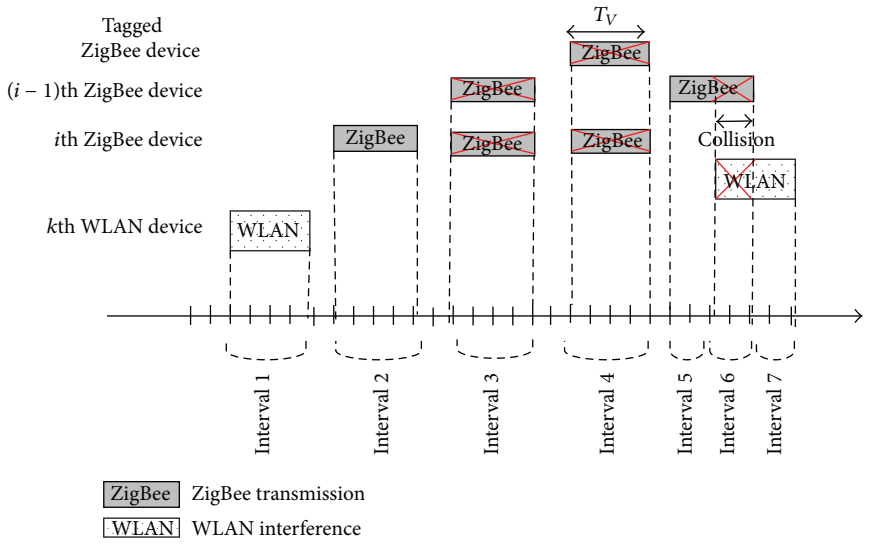


Figure 6: ZigBee transmission cases interfered with by WLAN.

length, and backoff unit duration. Then, two possible channel busy cases due to WLAN transmission can occur: (1) one ZigBee CCA duration is shorter than WLAN consecutive idle duration ($T_{\text{cca}} < \Psi_{\text{wl}}\sigma_{\text{wl}}$) and (2) one ZigBee CCA duration is longer than WLAN consecutive idle duration ($T_{\text{cca}} > \Psi_{\text{wl}}\sigma_{\text{wl}}$). If $T_{\text{cca}} < \Psi_{\text{wl}}\sigma_{\text{wl}}$, then ρ_{wl} is equal to WLAN channel activity. On the other hand, if $T_{\text{cca}} > \Psi_{\text{wl}}\sigma_{\text{wl}}$, then ρ_{wl} is equal to 1. Hence, ρ_{wl} is given by

$$\begin{aligned}\rho_{\text{wl}} &= \mathbb{P}\left\{T_{\text{cca}} < \Psi_{\text{wl}}\sigma_{\text{wl}}\right\} \\ &\cdot \left[\frac{\mathsf{p}_{s_{\text{wl}}}\left(T_{s_{\text{wl}}} + T_{\text{cca}}\right) + \left(1-\mathsf{p}_{s_{\text{wl}}}\right)\left(T_{c_{\text{wl}}} + T_{\text{cca}}\right)}{\mathbb{E}\left\{\Psi_{\text{wl}}\right\}\sigma_{\text{wl}} + \mathsf{p}_{s_{\text{wl}}}T_{s_{\text{wl}}} + \left(1-\mathsf{p}_{s_{\text{wl}}}\right)T_{c_{\text{wl}}}}\right] \\ &+ \mathbb{P}\left\{T_{\text{cca}} \geq \Psi_{\text{wl}}\sigma_{\text{wl}}\right\},\end{aligned} \tag{4}$$

where WLAN channel activity expressed in the first term is a function of successful transmission probability $\mathsf{p}_{s_{\text{wl}}}$, successful transmission duration $T_{s_{\text{wl}}}$, and collision duration $T_{c_{\text{wl}}}$ as well as σ_{wl}, T_{cca}, and $\mathbb{E}\{\Psi_{\text{wl}}\}$. Note that $\mathbb{E}\{\Psi_{\text{wl}}\}$ is a function of WLAN transmission probability κ_{wl} and the number of active WLAN devices n_{wl} as follows:

$$\mathbb{E}\left\{\Psi_{\text{wl}}\right\} = \frac{1}{1-\left(1-\kappa_{\text{wl}}\right)^{n_{\text{wl}}}} - 1. \tag{5}$$

We can also approximate $\mathbb{P}\{T_{\text{cca}} < \Psi_{\text{wl}}\sigma_{\text{wl}}\}$ as (see Appendix A)

$$\mathbb{P}\left\{T_{\text{cca}} < \Psi_{\text{wl}}\sigma_{\text{wl}}\right\} = \left(1-\kappa_{\text{wl}}\right)^{n_{\text{wl}}\lceil T_{\text{cca}}/\sigma_{\text{wl}}\rceil}, \tag{6}$$

where $\lceil x \rceil$ denotes the ceiling function of x.

Using (4)–(6), we have

$$\begin{aligned}&\rho_{\text{wl}} \\ &= \frac{\left(1-\kappa_{\text{wl}}\right)^{n_{\text{wl}}\lceil T_{\text{cca}}/\sigma_{\text{wl}}\rceil}\left[\mathsf{p}_{s_{\text{wl}}}T_{s_{\text{wl}}} + \left(1-\mathsf{p}_{s_{\text{wl}}}\right)T_{c_{\text{wl}}}\right]}{\left[1/\left(1-\left(1-\kappa_{\text{wl}}\right)^{n_{\text{wl}}}\right)-1\right]\sigma_{\text{wl}} + \mathsf{p}_{s_{\text{wl}}}T_{s_{\text{wl}}} + \left(1-\mathsf{p}_{s_{\text{wl}}}\right)T_{c_{\text{wl}}}} \\ &\quad + 1 - \left(1-\kappa_{\text{wl}}\right)^{n_{\text{wl}}\lceil T_{\text{cca}}/\sigma_{\text{wl}}\rceil}.\end{aligned} \tag{7}$$

To derive ρ_{zb}, the ZigBee transmissions in terms of the tagged ZigBee need to be investigated. We first define the *CCA-start probability* κ of a ZigBee in backoff states as

$$\begin{aligned}\kappa &= \frac{\sum_{i=0}^{m}\pi_{i,0}}{\sum_{i=0}^{m}\sum_{j=0}^{W_i-1}\pi_{i,j}} \\ &= \frac{2\left[1-\left(\rho+\zeta-\rho\zeta\right)^{m+1}\right]}{\sum_{i=0}^{m}\left(CW_0 2^{\eta_i}+1\right)\left(\rho+\zeta-\rho\zeta\right)^i} \\ &\quad \times \frac{1}{1-\left(\rho+\zeta-\rho\zeta\right)},\end{aligned} \tag{8}$$

where $\pi_{i,j}$ is the stationary probability of $s_{i,j}$ and η_i is the additional backoff exponent value of backoff stage i [2]. The denominator is a summation over backoff states ($\{s_{i,j} \mid i \in [0,m],\ j \in [0, CW_i - 1]\}$) since CCA-start probability assumes that a device is in the backoff states. $\eta_{\max}$ and $\eta_{\min}$ are the maximum and minimum backoff exponent values, respectively. Then, we have $\eta_i = \min\{i, \eta_{\max} - \eta_{\min}\}$. Due to $n-1$ other ZigBee transmissions, two possible channel busy events of the tagged ZigBee can occur: successful and collided transmissions of other ZigBees. In the successful transmission interval, only one of other ZigBees reaches the CCA-start state with probability $(n-1)\kappa(1-\kappa)^{n-1}$, and WLAN devices do not interfere for two consecutive CCAs

with probability $(1-\rho_{\text{wl}})(1-\zeta_{\text{wl}})$ and do not transmit during total ZigBee communication time with probability $(1-\kappa_{\text{wl}})^{\lceil L_{\text{tx}}(\sigma/\sigma_{\text{wl}})\rceil n_{\text{wl}}}$, where $L_{\text{tx}}(\sigma/\sigma_{\text{wl}})$ denotes total ZigBee communication time. In the collided transmission, at least two other ZigBee devices reach the CCA-start state simultaneously with probability $(1-\kappa)[1-(1-\kappa)^{n-1}-(n-1)\kappa(1-\kappa)^{n-2}]$, and WLAN devices do not interfere for two consecutive CCAs $(1-\kappa_{\text{wl}})^{\lceil L_{\text{tx}}(\sigma/\sigma_{\text{wl}})\rceil n_{\text{wl}}}$. Let p_t and p_s be transmission and successful transmission probabilities of ZigBees except the tagged ZigBee, respectively. Then, we have

$$\begin{aligned}\mathsf{p}_t &= (1-\kappa)\left[1-(1-\kappa)^{n-1}\right](1-\rho_{\text{wl}})(1-\zeta_{\text{wl}}),\\ \mathsf{p}_s &= \frac{(n-1)\kappa(1-\kappa)^{n-1}(1-\rho_{\text{wl}})(1-\zeta_{\text{wl}})(1-\kappa_{\text{wl}})^{\lceil(\lceil L_f\rceil+\lfloor\delta\rfloor+\lceil L_{\text{ack}}\rceil)(\sigma/\sigma_{\text{wl}})\rceil n_{\text{wl}}}}{\mathsf{p}_t},\end{aligned} \tag{9}$$

where L_f is the ZigBee frame length, δ is the acknowledgement waiting time, and L_{ack} is the acknowledgement frame length. $\lfloor x\rfloor$ denotes the floor function of x.

Consider that $\mathsf{T}_1, \mathsf{T}_2, \ldots$ is a sequence of intervals of successful transmissions of the tagged ZigBee, and $\mathsf{W}_1, \mathsf{W}_2, \ldots$ is a sequence of channel busy duration in $\mathsf{T}_1, \mathsf{T}_2, \ldots$, respectively. $\mathsf{T}_1, \mathsf{T}_2, \ldots$ is a sequence of positive independent and identically distributed random variables such that

$$0 < \mathbb{E}\{\mathsf{T}_i\} < \infty \tag{10}$$

and $\mathsf{W}_1, \mathsf{W}_2, \ldots$ is a sequence of random variables (rewards) satisfying

$$\mathbb{E}\{\mathsf{W}_i\} < \infty. \tag{11}$$

Let $\mathsf{Y}_t = \sum_{i=1}^{\mathsf{K}_t} W_i$ where $\mathsf{K}_t = \sup\{n : \mathsf{J}_n \le t\}$ and $\mathsf{J}_n = \sum_{i=1}^{n} \mathsf{T}_i$. Using the elementary renewal theorem for renewal reward processes, we have

$$\lim_{t\to\infty}\frac{1}{t}\mathbb{E}\{\mathsf{Y}_t\} = \frac{\mathbb{E}\{\mathsf{W}_1\}}{\mathbb{E}\{\mathsf{T}_1\}}. \tag{12}$$

Using (12), ρ_{zb} is given by

$$\rho_{\text{zb}} = \frac{\mathsf{p}_t\left[\mathsf{p}_s L_{\text{bs}} + (1-\mathsf{p}_s)L_{\text{bc}}\right]}{\mathsf{p}_t\left[\mathsf{p}_s L_s + (1-\mathsf{p}_s)L_c\right] + (1-\mathsf{p}_t)}, \tag{13}$$

where L_s and L_c are successful transmission and collision duration in ZigBee unit slots, respectively, and L_{bs} and L_{bc} are busy duration out of L_s and L_c, respectively.

$\rho_{\text{wl+zb}}$ is approximated as

$$\rho_{\text{wl+zb}} \approx \rho_{\text{zb}}\left[1 - \frac{\mathsf{U}_{\text{wl}}\left(1-\mathsf{U}_{\text{wl}}^{\lceil L_f\rceil+\lfloor\delta\rfloor+\lceil L_{\text{ack}}\rceil}\right)}{1-\mathsf{U}_{\text{wl}}} \cdot \frac{1}{\lceil L_f\rceil+\lfloor\delta\rfloor+\lceil L_{\text{ack}}\rceil}\right], \tag{14}$$

where $\mathsf{U}_{\text{wl}} = (1-\kappa_{\text{wl}})^{(\sigma/\sigma_{\text{wl}})n_{\text{wl}}}$ is the probability that n_{wl} WLAN devices do not transmit data during σ (see Appendix B). Substituting (7), (13), and (18) into (2), we finally get ρ.

For the second CCA, two possible busy events can occur: (i) $\Psi_{\text{wl}}\sigma_{\text{wl}} > \sigma + T_{\text{cca}}$, that is, WLAN has longer consecutive idle duration compared to a unit backoff slot plus one CCA duration of a ZigBee, and (ii) $T_{\text{cca}} \le \Psi_{\text{wl}}\sigma_{\text{wl}} \le \sigma + T_{\text{cca}}$, that is, WLAN consecutive idle duration is in the range from one ZigBee CCA duration to a ZigBee backoff unit slot plus one ZigBee CCA duration. Hence, we have

$$\begin{aligned}\zeta_{\text{wl}} \approx{}& \mathbb{P}\{\Psi_{\text{wl}}\sigma_{\text{wl}} > \lceil T_{\text{cca}}\rceil + T_{\text{cca}}\}\left(\frac{1}{1-\rho_{\text{wl}}}\right)\\ &\cdot\frac{\lceil T_{\text{cca}}\rceil}{\mathbb{E}\{\Psi_{\text{wl}}\}\sigma_{\text{wl}} + \mathsf{p}_{s_{\text{wl}}}T_{s_{\text{wl}}} + \left(1-\mathsf{p}_{s_{\text{wl}}}\right)T_{c_{\text{wl}}}}\\ &+\sum_{x=T_{\text{cca}}/\sigma_{\text{wl}}}^{(\lceil T_{\text{cca}}\rceil+T_{\text{cca}})/\sigma_{\text{wl}}}\mathbb{P}\{\Psi_{\text{wl}}=x\}\left(\frac{1}{1-\rho_{\text{wl}}}\right)\\ &\cdot\frac{(x\sigma_{\text{wl}}-T_{\text{cca}})}{\mathbb{E}\{\Psi_{\text{wl}}\}\sigma_{\text{wl}} + \mathsf{p}_{s_{\text{wl}}}T_{s_{\text{wl}}} + \left(1-\mathsf{p}_{s_{\text{wl}}}\right)T_{c_{\text{wl}}}}.\end{aligned} \tag{15}$$

Using the approximations of $\mathbb{P}\{\Psi_{\text{wl}}\sigma_{\text{wl}} > \lceil T_{\text{cca}}\rceil + T_{\text{cca}}\}$ and $\mathbb{P}\{\Psi_{\text{wl}} = x\}$ in Appendix A, we get ζ_{wl}

$$\begin{aligned}\zeta_{\text{wl}} \approx{}& \left(\frac{1}{1-\rho_{\text{wl}}}\right)\frac{(1-\kappa_{\text{wl}})^{n_{\text{wl}}\lceil(\lceil T_{\text{cca}}\rceil+T_{\text{cca}})/\sigma_{\text{wl}}\rceil}\lceil T_{\text{cca}}\rceil}{\mathbb{E}\{\Psi_{\text{wl}}\}\sigma_{\text{wl}} + \mathsf{p}_{s_{\text{wl}}}T_{s_{\text{wl}}} + \left(1-\mathsf{p}_{s_{\text{wl}}}\right)T_{c_{\text{wl}}}} + \left(\frac{1}{1-\rho_{\text{wl}}}\right)\\ &\cdot\frac{\sum_{x=T_{\text{cca}}/\sigma_{\text{wl}}}^{(\lceil T_{\text{cca}}\rceil+T_{\text{cca}})/\sigma_{\text{wl}}}(1-\kappa_{\text{wl}})^{n_{\text{wl}}(x-1)}\left[1-(1-\kappa_{\text{wl}})^{n_{\text{wl}}}\right](x\sigma_{\text{wl}}-T_{\text{cca}})}{\mathbb{E}\{\Psi_{\text{wl}}\}\sigma + \mathsf{p}_{s_{\text{wl}}}T_{s_{\text{wl}}} + \left(1-\mathsf{p}_{s_{\text{wl}}}\right)T_{c_{\text{wl}}}}.\end{aligned} \tag{16}$$

In addition,

$$\begin{aligned}\zeta_{\text{zb}} ={}& \left(\frac{1}{1-\rho_{\text{zb}}}\right)\\ &\cdot\frac{\mathsf{p}_t\left[\mathsf{p}_s L_{\text{is}} + (1-\mathsf{p}_s)L_{\text{ic}}\right]}{\mathsf{p}_t\left[\mathsf{p}_s L_s + (1-\mathsf{p}_s)L_c\right] + \kappa + (1-\kappa-\mathsf{p}_t)},\end{aligned} \tag{17}$$

where L_{is} and L_{ic} denote the duration during which the second busy CCA events occur out of L_s and L_c, respectively. The second CCA is considered to be busy during the first slot of data or the acknowledgement transmission in the successful transmission case (p_s) while it is considered to be busy, in the collision case ($1-\mathsf{p}_s$), during the first slot of data transmission. Hence, $L_{\text{is}} = 2\lceil L_{\text{cca}}\rceil$ and $L_{\text{ic}} = \lceil L_{\text{cca}}\rceil$.

Again, we have

$$\zeta_{\mathrm{wl+zb}} \approx \zeta_{\mathrm{zb}} \left[1 - \mathsf{p}_s \frac{\mathsf{U}_{\mathrm{wl}} \left(1 - \mathsf{U}_{\mathrm{wl}}^{L_{\mathrm{is}}}\right)}{\left(1 - \mathsf{U}_{\mathrm{wl}}\right)} \frac{1}{L_{\mathrm{is}}} - \left(1 - \mathsf{p}_s\right) \frac{\mathsf{U}_{\mathrm{wl}} \left(1 - \mathsf{U}_{\mathrm{wl}}^{L_{\mathrm{ic}}}\right)}{\left(1 - \mathsf{U}_{\mathrm{wl}}\right)} \frac{1}{L_{\mathrm{ic}}} \right], \tag{18}$$

where the second and third terms represent the ratios of simultaneous transmissions among ZigBee transmissions making the second CCA busy in the successful and collided transmission cases, respectively (see Appendix B). Substituting (16), (17), and (18) into (3), we finally get ζ.

5. Adaptive Interference Avoidance Algorithm

Our proposed algorithm adaptively controls ZigBee transmissions based on the amount of WLAN interference to maximize the performance of ZigBee network. Our proposed method basically assumes that WLAN devices highly contend for channel access. First, a WLAN AP estimates the WLAN channel activity ρ_{wl}. The WLAN channel activity ρ_{wl} is monitored by a WLAN AP. For the number of associated WLAN nodes, a WLAN AP can keep track of it. However, some associated WLAN nodes may be inactive while the others are active. Here, it is difficult for a WLAN AP to directly know about the number N_{wl} of active WLAN nodes. The channel activity is reflected in $\sum_{i=0}^{c-1} A[m]_i$ and $\sum_{i=0}^{c-1} B[m]_i$ in (21) and (22), which are used to calculate N_{wl} in (20). WLAN AP then informs ZigBee of N_{wl} and ρ_{wl} from which the PNC calculates the number N_{zb}^* of ZigBee devices as well as the length L_{zb}^* for each ZigBee frame. The PNC broadcasts N_{zb}^* and L_{zb}^* to ZigBee devices which decide if they send data or not considering N_{zb}^* and the total number of Zigbee devices. This situation can be feasibly given when there are devices having both WLAN and ZigBee modules in a network. If a ZigBee device transmits, it sends its frame after segmenting the frame into the length of L_{zb}^*. This procedure repeats periodically.

5.1. Autoregressive-Moving-Average (ARMA) Estimation of N_{wl}. N_{wl} is estimated using the following expression [34]:

$$N_{\mathrm{wl}} = \frac{\log\left(1 - p_{\mathrm{wl}}\right)}{\log\left(1 - \kappa_{\mathrm{wl}}\right)} + 1, \tag{19}$$

where κ_{wl} and p_{wl} are WLAN transmission and collision probabilities, respectively. The estimation of κ_{wl} and p_{wl} is derived by ARMA(β,c) [57]. First, κ_{wl} is estimated as follows:

$$\widehat{\kappa}_{\mathrm{wl}}[m+1] = \beta \widehat{\kappa}_{\mathrm{wl}}[m] + \frac{(1-\beta)}{c} \sum_{i=0}^{c-1} A[m]_i, \tag{20}$$

where c and β are the number of measured samples and ARMA model parameter, respectively. $\kappa_{\mathrm{wl}}[m]$ is transmission probability in the mth beacon interval. $A[m]_i$ is 1 only if AP observes the beginning of the WLAN station's transmission at the ith slot of the mth beacon interval. Otherwise, $A[m]_i$ is 0.

Collision probability p_{wl} is similarly estimated as follows:

$$\widehat{p_{\mathrm{wl}}}[m+1] = \beta \widehat{p_{\mathrm{wl}}}[m] + \frac{(1-\beta)}{c} \sum_{i=0}^{c-1} B[m]_i, \tag{21}$$

where $p_{\mathrm{wl}}[m]$ is collision probability in the mth beacon interval and $B[m]_i$ is 0 when the WLAN station observes the channel is idle or successfully transmits its frame at the ith slot of the mth beacon interval. On the other hand, $B[m]_i$ is 1 when the WLAN station observes the channel is busy or transmits with collisions. We estimate p_{wl} and κ_{wl} periodically and recursively at the end of every beacon interval. When p_{wl} is equal to 0, N_{wl} is estimated to be 1.

5.2. Determination of N_{zb}^* and L_{zb}^*. ZigBee determines N_{zb}^* and L_{zb}^* which maximize ZigBee performance measures such as throughput, energy consumption, or delay.

The normalized throughput S is defined as

$$\mathsf{S} = \frac{\text{successfully transmitted bits in a ZigBee network}}{\text{observation time (secs)}} \times \frac{1}{R}, \tag{22}$$

where R denotes ZigBee PHY data rate. Regarding the average time of state transition as a renewal period, $\mathbb{E}\{\mathsf{S}\}$ can be expressed as [32]

$$\mathbb{E}\{\mathsf{S}\} = \frac{n\kappa(1-\kappa)^{n-1}(1-\rho)(1-\zeta)\gamma L_p}{(1-\kappa) + \kappa\rho + 2\kappa(1-\rho)\zeta + \kappa(1-\rho)(1-\zeta)\{\gamma L_s + (1-\gamma)L_c\}}, \tag{23}$$

where L_p is payload length in slots and γ is successful frame transmission probability after two successful CCAs. Since ZigBees sense a shared channel for only two successful CCAs, the frame successful transmission after CCAs is only dependent on WLAN transmissions. Hence, considering that $\lceil \lceil L_{\mathrm{tx}} \rceil (\sigma/\sigma_{\mathrm{wl}}) \rceil$ is the number of WLAN slots within L_{tx}, γ is expressed as

$$\gamma = \left(1 - \kappa_{\mathrm{wl}}\right)^{\lceil \lceil L_{\mathrm{tx}} \rceil (\sigma/\sigma_{\mathrm{wl}}) \rceil N_{\mathrm{wl}}}, \tag{24}$$

where L_{tx} and σ_{wl} are transmission length in slots and WLAN's unit time, respectively.

The energy consumption E is defined as the amount of energy consumed per transmission unit slot by a ZigBee

network. $\mathbb{E}\{\mathsf{E}\}$ is expressed as [32]

$$\mathbb{E}\{\mathsf{E}\} = \frac{\kappa\rho T_{\text{cca}} E_{\text{rx}} + \kappa(1-\rho)\zeta T_{\text{cca}} E_{\text{rx}} + \kappa(1-\rho)(1-\zeta)\{\gamma E_s + (1-\gamma)E_c\}}{\kappa(1-\rho)(1-\zeta)\gamma L_p}, \tag{25}$$

where E_{rx}, E_s, and E_c are consumed energies for reception, successful transmission, and collision, respectively.

Access delay D is defined as elapsed interval from the time when the frame reaches the head-of-line of a transmitter's buffer and the time when the frame arrives at a receiver without collision. By Little's law [35], $\mathbb{E}\{\mathsf{D}\}$ is given as

$$\mathbb{E}\{\mathsf{D}\} = \frac{n}{\mathbb{E}\{\mathsf{S}\}/L_p} \cdot \sigma, \tag{26}$$

where $\mathbb{E}\{\mathsf{S}\}/L_p$ represents ZigBee frame delivery rate. Throughput, energy consumption, and delay are affected by WLAN parameters, for example, N_{wl} and ρ_{wl} (or κ_{wl}) as shown in (23), (25), and (26). After receiving $\widehat{N}_{\text{wl}}$ and $\widehat{\kappa_{\text{wl}}}$ from a WLAN AP, the ZigBee PNC finds N^*_{zb} and L^*_{zb} that maximize required performance index, for example, throughput, energy consumption, or delay, depending on service requirements. For example, if $\widehat{N}_{\text{wl}}$ and $\widehat{\kappa_{\text{wl}}}$ are 3 and 0.12 with a constraint that energy consumption should be minimized, then the ZigBee PNC finds N^*_{zb} and L^*_{zb} minimizing (25). And it can be a problem if the energy consumption in calculating the number of interference nodes, N^*_{zb} and L^*_{zb}, surpasses the transmission energy saved by our proposed algorithm. However, the relatively stable nature of WLAN condition enables us to assume that the calculation does not occur too frequently. To reduce the computational complexity of the algorithm, we made a matching table in advance, which has inputs of N_{wl} and ρ_{wl} and gives outputs of N^*_{zb} and L^*_{zb} from the table.

6. Numerical Result

We configured coexisting ZigBee and WLAN networks using OPNET Modeler 14.5 as shown in Figure 7 and Matlab. A ZigBee network interfered with by saturated and unsaturated WLAN nodes is considered. Here, all the ZigBee devices in a network are considered to be affected by WLAN interference.

In our interference analysis, ZigBee devices are assumed to always have frames to transmit while IEEE 802.11b/g WLAN devices are considered to have frames that arrive at their buffers in a Poisson manner with the intensity of λ_{wl}. Hence, when we define q_{wl} as the probability of WLAN traffic generation in each slot, $\mathsf{q}_{\text{wl}} = \mathsf{Exp}(-\lambda_{\text{wl}}T)$. This analysis can be regarded as saturation mode analysis by increasing λ_{wl} and q_{wl}. κ_{wl} is expressed as in [41]:

$$\kappa_{\text{wl}} = \pi_{0,0}^{e_{\text{wl}}} \left(\frac{\mathsf{q}_{\text{wl}}^2 W_{0_{\text{wl}}}}{(1-\mathsf{p}_{\text{wl}})(1-\mathsf{q}_{\text{wl}})\left(1-(1-\mathsf{q}_{\text{wl}})^{W_{0_{\text{wl}}}}\right)} - \frac{\mathsf{q}_{\text{wl}}^2(1-\mathsf{p}_{\text{wl}})}{1-\mathsf{q}_{\text{wl}}} \right), \tag{27}$$

where $\pi_{0,0}^{e_{\text{wl}}}$ is stationary probability of a device which has a backoff counter value of zero with no waiting frame. p_{wl} is the collision probability of a device. The expected slot time $\mathbb{E}\{\mathsf{T}\}$ can be derived as

$$\mathbb{E}\{\mathsf{T}\} = \left(1-\mathsf{p}_{\text{tr}_{\text{wl}}}\right)\sigma_{\text{wl}} + \mathsf{p}_{\text{tr}_{\text{wl}}}\mathsf{p}_{s_{\text{wl}}}T_{s_{\text{wl}}} + \mathsf{p}_{\text{tr}_{\text{wl}}}\mathsf{p}_{c_{\text{wl}}}T_{c_{\text{wl}}}, \tag{28}$$

where $\mathsf{p}_{\text{tr}_{\text{wl}}}$, $\mathsf{p}_{s_{\text{wl}}}$, and $\mathsf{p}_{c_{\text{wl}}}$ are transmission, success, and collision probabilities in a WLAN network, respectively, and $\mathsf{p}_{\text{tr}_{\text{wl}}} = 1-(1-\kappa_{\text{wl}})^{n_{\text{wl}}}$, $\mathsf{p}_{s_{\text{wl}}} = n_{\text{wl}}\kappa_{\text{wl}}(1-\kappa_{\text{wl}})^{n_{\text{wl}}-1}$, and $\mathsf{p}_{c_{\text{wl}}} = 1-(1-\kappa_{\text{wl}})^{n_{\text{wl}}} - n_{\text{wl}}\kappa_{\text{wl}}(1-\kappa_{\text{wl}})^{n_{\text{wl}}-1}$. Table 1 shows our WLAN and ZigBee parameter settings [17, 20, 21]. $L_s = 2\lceil L_{\text{cca}}\rceil + L_f + \lfloor\delta\rfloor + \lceil L_{\text{ack}}\rceil$, $L_c = 2\lceil L_{\text{cca}}\rceil + L_f$, and $L_{\text{bs}} = L_{\text{bc}} = L_f$. E_s and E_c are set to $L_f E_{\text{tx}} + (\lfloor\delta\rfloor + \mathsf{T}_{\text{ack}})E_{\text{rx}}$ and $L_f E_{\text{tx}} + (\lfloor\delta\rfloor + \mathsf{T}_{\text{ack}})E_{\text{rx}}$, respectively.

Our analysis framework is verified by comparing throughput, delay, and energy consumption obtained from our framework with those from simulation results. Each simulation point is obtained by averaging over fifteen simulation run results with the duration of 600 seconds. The range bars are also drawn on the plot. Figure 8 shows a ZigBee network's normalized throughput $\mathbb{E}\{\mathsf{S}\}$ with varying WLAN interference load λ_{wl} when n and n_{wl} are fixed to 25 and 3. The analytical results obtained from the proposed model are validated and agree well with the simulation results. When the length of a ZigBee frame L_f is equal to 8 and λ_{wl} is set to 0.047, $\mathbb{E}\{\mathsf{S}\}$ is equal to 0.09. However, if the ZigBee network is interfered with by the WLAN with $\lambda_{\text{wl}} = 0.116$, $\mathbb{E}\{\mathsf{S}\}$ decreases to 0.03. Fixing λ_{wl} to 0.047, $\mathbb{E}\{\mathsf{S}\}$ increases as $L_{f,\text{slot}}$ gets larger because WLAN interference is not severe. However, when $\lambda_{\text{wl}} = 0.139$, as L_f increases from 8 to 12, $\mathbb{E}\{\mathsf{S}\}$ does not significantly change since the ZigBee frame is exposed to severe WLAN interference which causes more collisions between ZigBee and WLAN transmissions. Here, $\mathbb{E}\{\mathsf{S}\}$ exhibits a steeper decrease as L_f gets larger. Figures 10 and 12 show mean energy consumption $\mathbb{E}\{\mathsf{E}\}$ and access delay $\mathbb{E}\{\mathsf{D}\}$ for varying λ_{wl}. Similar to $\mathbb{E}\{\mathsf{S}\}$, as L_f gets larger, $\mathbb{E}\{\mathsf{E}\}$ and $\mathbb{E}\{\mathsf{D}\}$ abruptly get worse. Figures 9, 11, and 13 show $\mathbb{E}\{\mathsf{S}\}$, $\mathbb{E}\{\mathsf{E}\}$, and $\mathbb{E}\{\mathsf{D}\}$ of a ZigBee network when n_{wl} increases from 3 to 6 with the fixed total amount of WLAN network load, λ_{wl}. The ZigBee performance is slightly degraded when n_{wl} increases from 3 to 6 since more WLAN devices generate less ZigBee's transmission opportunities due to WLAN devices' increased contention on the shared channel. However, this degradation is not considerable since the total traffic load λ_{wl} is fixed and shared by WLAN devices.

For the saturated WLAN mode, the estimation of N_{wl} is done by simply measuring κ_{wl} and p_{wl}. Figure 7 shows a ZigBee network interfered with by WLAN interferers, where six Zigbee devices always have frames to transmit to a coordinator while WLAN transmissions are simply modeled

Table 1: WLAN and ZigBee related parameter values.

Parameter	Value	Description
E_{rx}	0.0113472 mJ	Energy consumption for ZigBee to receive (mJ)
E_{tx}	0.0100224 mJ	Energy consumption for ZigBee to transmit (mJ)
L_{ack}	1.1 slots	Length of Ack frame in ZigBee
L_{cca}	0.4 slots	One ZigBee CCA duration
L_f	4~20 slots	Length of a frame in ZigBee
L_{nack}	1.1 slots	Length of Nack duration in ZigBee
L_p	$L_f \times 80 - 120$ bits	Length of payload in ZigBee (bits)
$T_{coll_{wl}}$	944 μs	Length of collided transmission in WLAN (sec)
$T_{p_{wl}}$	364 μs	Length of payload in WLAN (sec)
$T_{succ_{wl}}$	944 μs	Length of successful transmission in WLAN (sec)
δ	1 slot	Duration of Ack wait in ZigBee
σ	320 μs	Length of one backoff unit in ZigBee (sec)
σ_{wl}	20 μs	Unit slot length of one backoff unit in WLAN (sec)

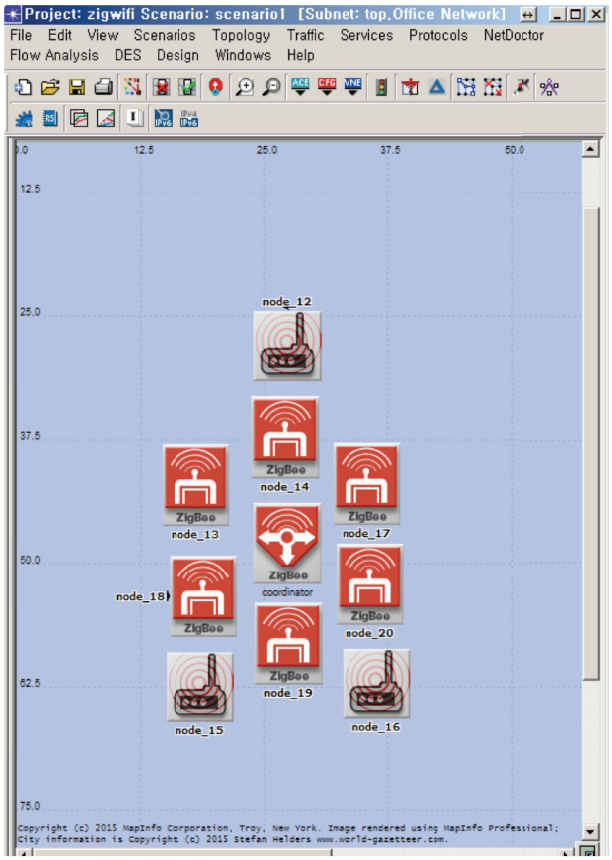


Figure 7: Our test coexisting environment.

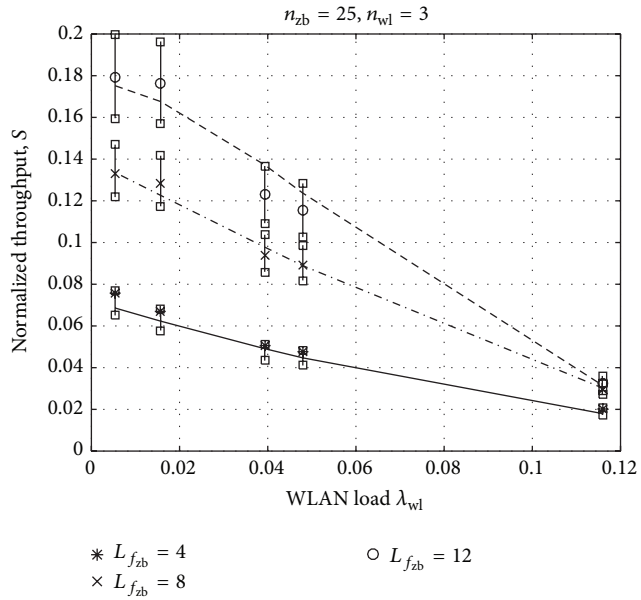


Figure 8: Throughput of a ZigBee network interfered with by WLAN devices ($n_{wl} = 3$).

by the M/G/1 model. Here, the PNC is considered to be equipped with WLAN AP functionality. Figures 14(a) and 14(b) show $\mathbb{E}\{S\}$ of a ZigBee network, the former without our proposed algorithm and the latter with the algorithm. We initially set the number n_{wl} of WLAN devices to 0. We sequentially added more WLAN interference load by increasing n_{wl} to 1, 2, and 3, respectively, and set n_{wl} back to 0. Here, the proposed algorithm focuses on controlling the ZigBee frame length L_{zb} without controlling n_{zb}, in order to minimize the algorithm computational complexity. The length of ZigBee frames is initially set to 1600 bits. The proposed algorithm shows consequently higher throughput in the overall range of n_{wl}. For every 5 minutes, the avoidance algorithm shows $\mathbb{E}\{S\}$ around 170,000, 0, 0, 0, and 170,000 for 0–5, 5–10, 10–15, 15–20, and 20–25 minutes' intervals, respectively, and the ZigBee operation without the avoidance algorithm gives the same.

For the nonsaturated WLAN mode, the estimation of N_{wl} needs additional information such as a WLAN traffic model. However, this additional information about the WLAN traffic model is difficult to be known in advance. As mentioned, hence, our model assumes that WLAN devices

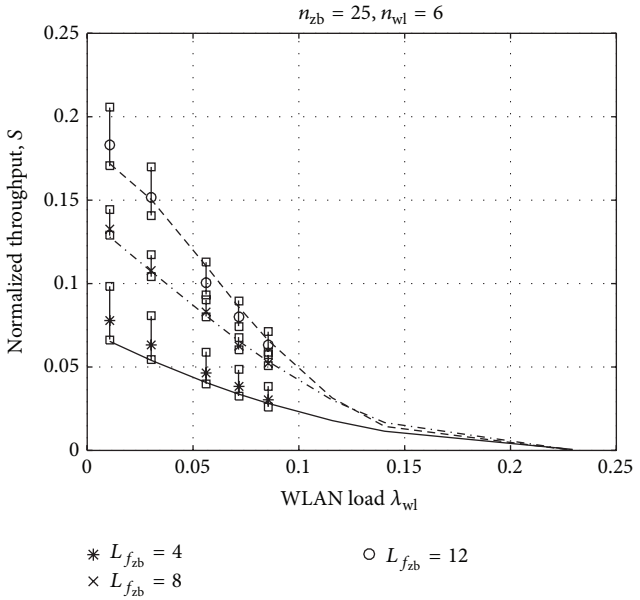


Figure 9: Throughput of a ZigBee network interfered with by WLAN devices ($n_{wl} = 6$).

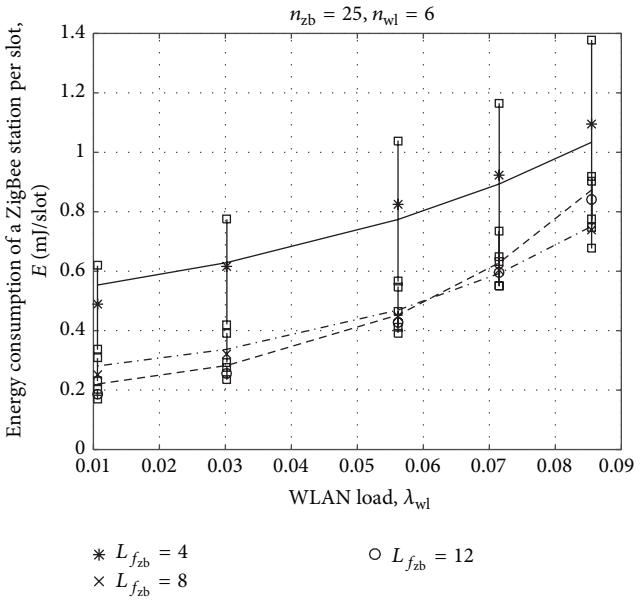


Figure 11: Energy consumption of a ZigBee network interfered with by WLAN devices ($n_{wl} = 6$).

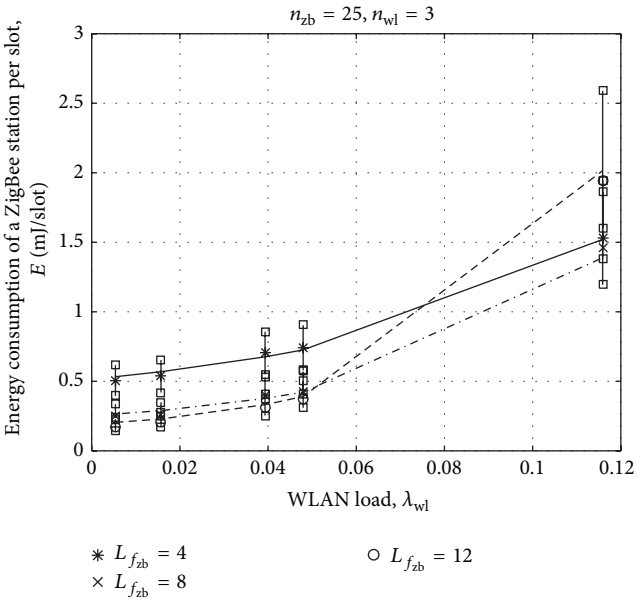


Figure 10: Energy consumption of a ZigBee network interfered with by WLAN devices ($n_{wl} = 3$).

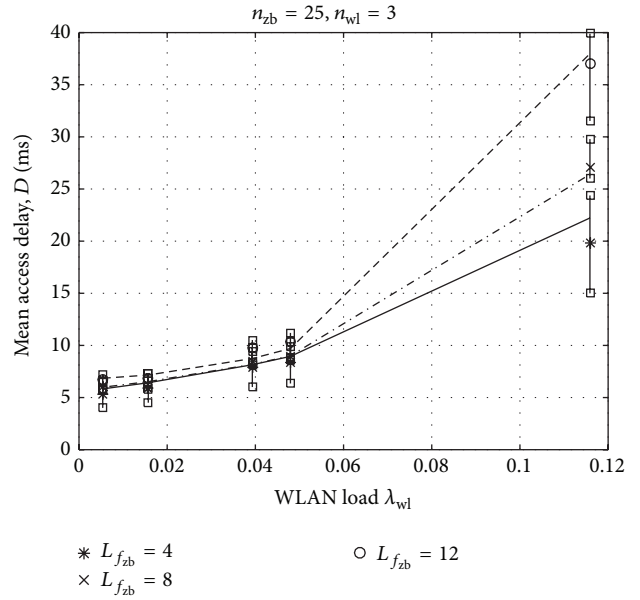


Figure 12: Delay of a ZigBee network interfered with by WLAN devices ($n_{wl} = 3$).

highly contend for channel access. The number of interfering WLAN devices is increased by one (from zero to three) every 5 minutes as in the saturated WLAN mode. The length of WLAN frames is set to 4800 μs with input load of 0.04 while that of ZigBee frames is initially set to 1600 bits. Here, the proposed algorithm focuses on adapting this length of ZigBee frames L_{zb} to measured WLAN interference with n_{zb} maintained. The throughput of the ZigBee network without interference avoidance algorithms is around 170,000, 130,000, 100,000, 70,000, and 170,000 bits/sec for 0–5, 5–10, 10–15, 15–20, and 20–25 minutes' intervals, respectively, as shown in Figure 15(a). Meanwhile, the proposed avoidance algorithm enhances the performance of the ZigBee network by showing better throughput 170,000, 140,000, 120,000, 105,000, and 170,000 bits/sec for 0–5, 5–10, 10–15, 15–20, and 20–25 minutes' intervals, respectively, as shown in Figure 15(b). There is no error in measuring N_{wl} during 5–10 minutes' interval since N_{wl} is equal to one. However, errors are introduced in measuring N_{wl} during 10–15 and 15–20 minutes' intervals,

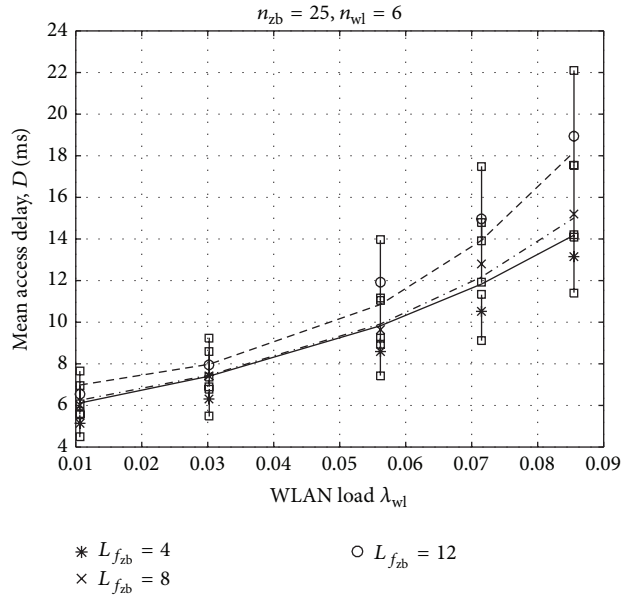
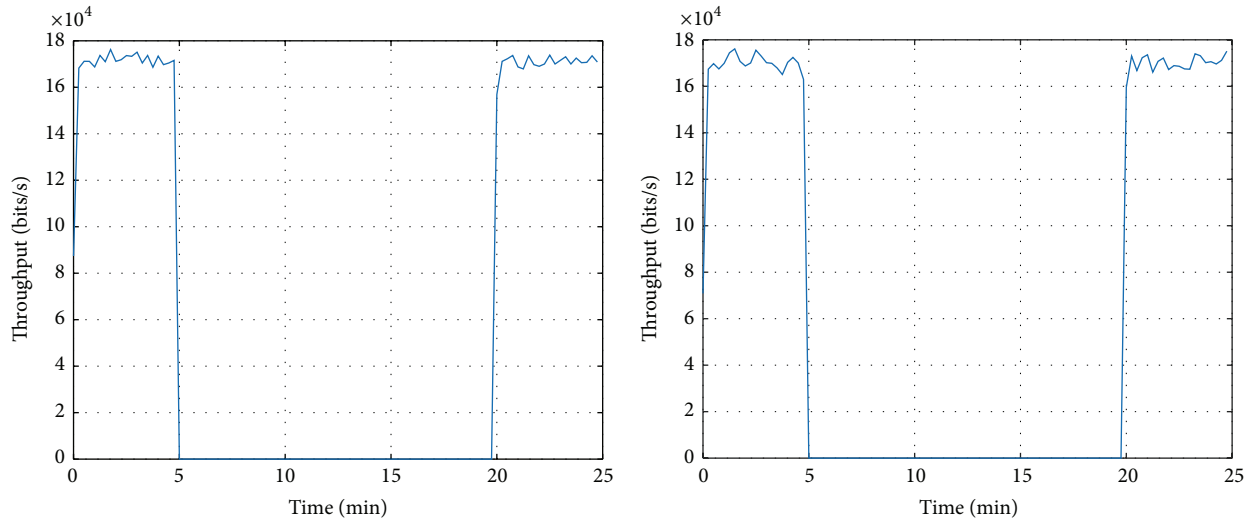


Figure 13: Delay of a ZigBee network interfered with by WLAN devices ($n_{wl} = 6$).



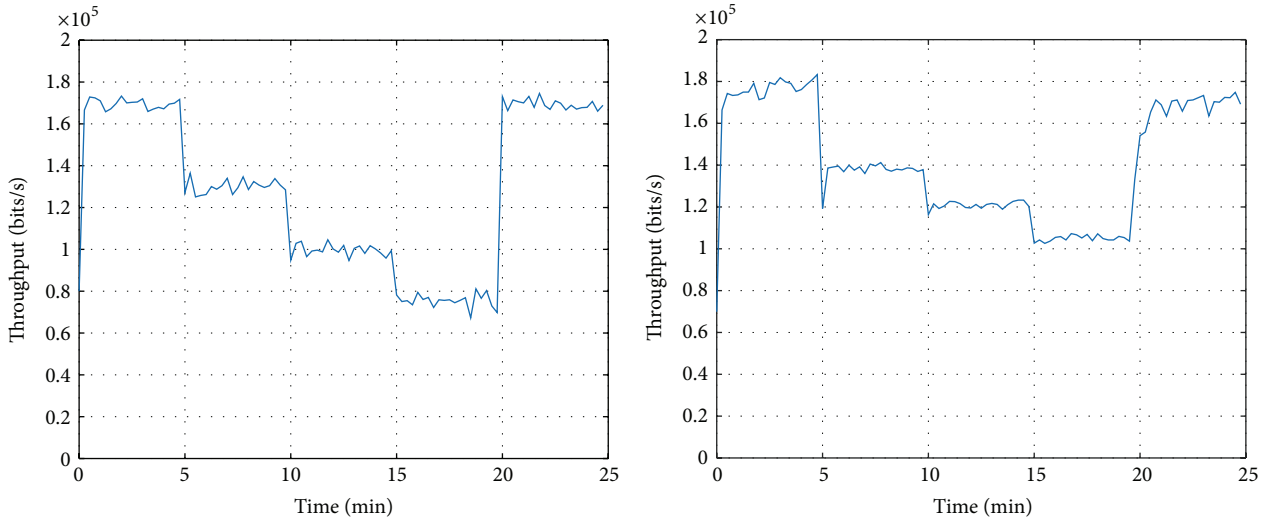
(a) Conventional algorithm (b) Proposed algorithm

Figure 14: Throughput of a ZigBee network with conventional and proposed algorithms interfered with by WLAN in the saturation mode.

that is, three and four, respectively, due to frequent collisions from hidden WLAN nodes. Since the optimum throughput of around 170,000, 145,000, 125,000, 105,000, and 170,000 coming from the accurate estimation of N_{wl} is higher than the throughput of our proposed algorithm, it gives better results if we can accurately measure N_{wl}.

7. Conclusion

In this paper, we have proposed a unified analysis framework for the ZigBee operation in a ZigBee network interfered with by heterogeneous WLAN networks. Moreover, we proposed an efficient WLAN interference avoidance algorithm for a ZigBee network which controls ZigBee frame length and devices based on the measured WLAN interference in an adaptive way. WLAN interferences are modeled based on the current IEEE 802.11 to consider realistic effects of interference on a ZigBee network's performance while a ZigBee network is also modeled based on the current IEEE 802.15.4 with a Markov chain concept. The simulation results show a close agreement to the analytical results obtained from our framework. The proposed interference avoidance algorithm has shown the improvement of ZigBee networks' performance by adapting the ZigBee frame length to the WLAN interference level. The simulation results show that the proposed and conventional algorithms give similar performance when the WLAN interferers in the saturated mode interfere with ZigBee networks. However, when the number of WLAN



(a) Conventional algorithm (b) Proposed algorithm

FIGURE 15: Throughput of a ZigBee network with conventional and proposed algorithms interfered with by WLAN in the nonsaturation mode.

interferers is in the nonsaturated mode, the proposed algorithm gives better ZigBee performance than the conventional algorithm. In particular, as the number of nonsaturated WLAN interferers with the input load of 0.04 increases, the proposed algorithm shows a small drop in performance while the conventional algorithm does a large drop. This is due to the algorithm's operation of adapting the length of ZigBees' frames to the measured WLAN interference.

We expect that the proposed analysis framework can be utilized in predicting the performance of ZigBee networks in the presence of heterogeneous WLAN networks as well as design of the parameter settings for efficient ZigBee communication. Also, our proposed unified analysis of a ZigBee network can be applied in predicting and designing various types of coexisting heterogeneous communication networks.

Appendices

A. Approximation of $\mathbb{P}\{\Psi_{\text{wl}}\sigma_{\text{wl}} \le \mathsf{T}_{\text{cca}}\}$, $\mathbb{P}\{\Psi_{\text{wl}}\sigma_{\text{wl}} > \lceil \mathsf{T}_{\text{cca}} \rceil + \mathsf{T}_{\text{cca}}\}$, and $\mathbb{P}\{\Psi_{\text{wl}} = x\}$

$\mathbb{P}\{\Psi_{\text{wl}}\sigma_{\text{wl}} \le \mathsf{T}_{\text{cca}}\}$ can be approximated to $\mathbb{P}\{\Psi_{\text{wl}} \le \lceil \mathsf{T}_{\text{cca}}/\sigma_{\text{wl}} \rceil\}$. $\mathbb{P}\{\Psi_{\text{wl}} \le \lceil \mathsf{T}_{\text{cca}}/\sigma_{\text{wl}} \rceil\}$ means the number of WLAN consecutive idle slots is equal to or smaller than the number of slots, that is, $\mathsf{T}_{\text{cca}}/\sigma_{\text{wl}}$. This can be derived by the summation of all the probabilities, from the probability that WLAN transmits its frame directly at the first slot to the probability that WLAN transmits at the $\lceil \mathsf{T}_{\text{cca}}/\sigma_{\text{wl}} \rceil$th slot as follows:

$$\begin{aligned}\mathbb{P}\left\{\Psi_{\text{wl}}\sigma_{\text{wl}} \le T_{\text{cca}}\right\} &\approx \mathbb{P}\left\{\Psi_{\text{wl}} \le \left\lceil \frac{T_{\text{cca}}}{\sigma_{\text{wl}}} \right\rceil\right\} \\ &= \left\{1-\left(1-\kappa_{\text{wl}}\right)^{n_{\text{wl}}}\right\} \sum_{i=0}^{\lceil T_{\text{cca}}/\sigma_{\text{wl}}\rceil - 1} \left\{\left(1-\kappa_{\text{wl}}\right)^{n_{\text{wl}}}\right\}^{i} \\ &= \left\{1-\left(1-\kappa_{\text{wl}}\right)^{n_{\text{wl}}}\right\} \frac{\left\{1-\left(1-\kappa_{\text{wl}}\right)^{n_{\text{wl}}}\right\}^{\lceil T_{\text{cca}}/\sigma_{\text{wl}}\rceil}}{1-\left(1-\kappa_{\text{wl}}\right)^{n_{\text{wl}}}} \\ &= 1-\left(1-\kappa_{\text{wl}}\right)^{n_{\text{wl}}\lceil T_{\text{cca}}/\sigma_{\text{wl}}\rceil}.\end{aligned} \tag{A.1}$$

Similarly, $\mathbb{P}\{\Psi_{\text{wl}}\sigma_{\text{wl}} > \lceil T_{\text{CCA}_{\text{wl}}} \rceil + T_{\text{CCA}}\}$ and $\mathbb{P}\{\Psi_{\text{wl}} = x\}$ can be expressed as

$$\begin{aligned}&\mathbb{P}\left\{\Psi_{\text{wl}}\sigma_{\text{wl}} > \lceil T_{\text{cca}} \rceil + T_{\text{cca}}\right\} \\ &\quad\approx \left(1-\kappa_{\text{wl}}\right)^{n_{\text{wl}}\lceil (\lceil T_{\text{cca}} \rceil + T_{\text{CCA}})/\sigma_{\text{wl}}\rceil}, \\ &\mathbb{P}\left\{\Psi_{\text{wl}} = x\right\} \approx \left\{\left(\kappa_{\text{wl}}\right)^{n_{\text{wl}}}\right\}^{x-1}\left\{1-\left(1-\kappa_{\text{wl}}\right)^{n_{\text{wl}}}\right\}.\end{aligned} \tag{A.2}$$

B. Approximation of $\rho_{\text{wl+zb}}$

We define U_{wl} as the probability that none of n_{wl} WLAN devices interfere with ZigBee data transmissions during a ZigBee unit slot, given that the previous slot was not occupied by the transmission of WLAN devices. U_{wl} can be expressed as $\{(1-\kappa_{\text{wl}})^{\sigma/\sigma_{\text{wl}}}\}^{n_{\text{wl}}}$, where $\sigma/\sigma_{\text{wl}}$ represents the number of WLAN backoff unit slots in a ZigBee unit backoff slot. When the length of a frame is denoted by $L_{f_x} = \lceil L_f \rceil + \lfloor \delta \rfloor + \lceil L_{\text{ack}} \rceil$, the average fraction $\bar{z}$ of the collided part out of L_{f_x} is expressed as

$$\begin{aligned}\bar{\mathsf{z}} = L_{f_x} - \Big\{&\mathsf{U}_{\text{wl}}\left(1-\mathsf{U}_{\text{wl}}\right) + 2\mathsf{U}_{\text{wl}}^{2}\left(1-\mathsf{U}_{\text{wl}}\right) + \cdots \\ &+ \left(L_{f_x}-1\right)\mathsf{U}_{\text{wl}}^{L_{f_x}-1}\left(1-\mathsf{U}_{\text{wl}}\right) + L_{f_x}\mathsf{U}_{\text{wl}}^{L_{f_x}}\Big\}.\end{aligned} \tag{B.1}$$

Then $\bar{\mathsf{z}}$ is equal to $L_{f_x} - \mathsf{X}$, where

$$\begin{aligned}\mathsf{X} = &\mathsf{U}_{\text{wl}}\left(1-\mathsf{U}_{\text{wl}}\right) + 2\mathsf{U}_{\text{wl}}^{2}\left(1-\mathsf{U}_{\text{wl}}\right) + \cdots \\ &+ \left(L_{f_x}-1\right)\mathsf{U}_{\text{wl}}^{L_{f_x}-1}\left(1-\mathsf{U}_{\text{wl}}\right) + L_{f_x}\mathsf{U}_{\text{wl}}^{L_{f_x}}.\end{aligned} \tag{B.2}$$

Rearranging X yields (B.3):

$$\begin{aligned}(1-\mathsf{U}_{\mathrm{wl}})\,\mathsf{X} &= \mathsf{U}_{\mathrm{wl}}(1-\mathsf{U}_{\mathrm{wl}}) + \mathsf{U}_{\mathrm{wl}}^{2}(1-\mathsf{U}_{\mathrm{wl}}) + \cdots \\ &\quad + \mathsf{U}_{\mathrm{wl}}^{L_{fx}-1}(1-\mathsf{U}_{\mathrm{wl}}) + \mathsf{U}_{\mathrm{wl}}^{L_{fx}}(1-\mathsf{U}_{\mathrm{wl}}).\end{aligned} \tag{B.3}$$

Finally, X is derived as

$$\begin{aligned}\mathsf{X} &= \mathsf{U}_{\mathrm{wl}} + \mathsf{U}_{\mathrm{wl}}^{2} + \cdots + \mathsf{U}_{\mathrm{wl}}^{L_{fx}-1} + \mathsf{U}_{\mathrm{wl}}^{L_{fx}} \\ &= \frac{\mathsf{U}_{\mathrm{wl}}\left(1-\mathsf{U}_{\mathrm{wl}}^{L_{fx}}\right)}{(1-\mathsf{U}_{\mathrm{wl}})}.\end{aligned} \tag{B.4}$$

Since $\rho_{\mathrm{wl+zb}}$ is defined as the collided ratio due to simultaneous ZigBee and WLAN transmissions, $\rho_{\mathrm{wl+zb}} = \rho\overline{z}/L_{f_x}$.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Endnotes

1. This assumption does not affect the original ZigBee network operation since the tagged ZigBee in the states of $j > 0$ does not cease to decrease its backoff counter even when the channel is sensed to be busy.
2. If the Markov chain is time-homogeneous, irreducible, positive recurrent, and aperiodic, then the chain converges to the stationary distribution regardless of its initial condition [55]. The stationary distribution $\pi_{i,j}$ satisfies the equation

$$\boldsymbol{\pi} = \boldsymbol{\pi}\mathbf{P},$$

where $\boldsymbol{\pi} = [\pi_{i,j}]$ and $\mathbf{P}$ is state transition probability matrix.

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