Joint Channel Allocation and Routing for ZigBee/Wi-Fi Coexistent Networks

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SUMMARY With the widespread diffusion of Internet of Things (IoT), the number of applications using wireless sensor devices is increasing, and Quality of Service (QoS) required for these applications is diversifying. Thus, it becomes difficult to satisfy a variety of QoS with a single wireless system, and many kinds of wireless systems are working in the same domains; time, frequency, and place. This paper considers coexistence environments of ZigBee and Wi-Fi networks, which use the same frequency band channels, in the same place. In such coexistence environments, ZigBee devices suffer radio interference from Wi-Fi networks, which results in severe ZigBee packet losses because the transmission power of Wi-Fi is much higher than that of ZigBee. Many existing methods to avoid interference from Wi-Fi networks focus on only one of time, frequency, or space domain. However, such avoidance in one domain is insufficient for near future IoT environments where more ZigBee devices and Wi-Fi stations transfer more amount of data. Therefore, in this paper, we propose joint channel allocation and routing in both frequency and space domains. Finally, we show the effectiveness of the proposed method by computer simulation.

key words: ZigBee, Wi-Fi, channel allocation, routing

1. Introduction

Recently, by the improvement of sensing technology and the reduction of device cost, more and more wireless sensor devices automatically communicate with each other in homes, buildings, cars, factories and so on, creating what is called Internet of Things (IoT) [1], [2]. For instance, environmental monitoring, industrial automation, health care and so on are realized with IoT [3]–[6].

With the widespread diffusion of IoT, the numbers of wireless sensor devices and applications using such devices are increasing, and Quality of Service (QoS) required for these applications is diversifying. Thus, it becomes difficult that a single wireless system satisfies a variety of QoS with constraints on devices (e.g., energy consumption, CPU performance and so on).

Thus, it becomes important that many kinds of wireless systems are working in a same place [7]. However, in such coexistence environments, communication quality deteriorates because wireless networks do not assume that they coexist with other kinds of wireless networks on the same frequency band (e.g., unlicensed band). Therefore, an effective interference mitigation mechanism is needed [8]–[10].

For IoT, ZigBee [11] is used in various environments and many ZigBee applications are developed [12]–[14]. On the other hand, Wi-Fi [15] has been already used very widely. Thus, the coexistence between ZigBee and Wi-Fi, both of which use 2.4 GHz band channels, is increasing. In such coexistence environments, ZigBee devices suffer radio interference from Wi-Fi networks, which results in severe ZigBee packet losses because the transmission power of Wi-Fi is much higher than that of ZigBee [16].

Radio interference avoidance in ZigBee networks from Wi-Fi networks has been already studied in one of time, frequency, or space domain [17]–[32]. However, interference avoidance only in either time or frequency domain is insufficient for near future IoT environments where more ZigBee devices and Wi-Fi stations transfer more amount of data. This is because the interference avoidance in frequency domain consumes channel resources by ZigBee devices’ frequent channel switching. Also in time domain, more ZigBee packets concentrate on specific durations during which Wi-Fi packets are not transferred, which results in frequent collisions among ZigBee packets. In space domain, some works establish ZigBee packet forwarding routes to avoid radio interference [31], [32]. However, the computational load at each device is increased, which results in difficulty of implementation on ZigBee devices whose computational resources and power supply are limited.

Therefore, as a realistic solution to avoid radio interference sufficiently from Wi-Fi networks, this paper proposes joint channel allocation and routing. Specifically, the optimal ZigBee channel is decided and allocated in the unit of sub-tree that is composed of the root ZigBee device, directly connected to the sink, and the descendant ZigBee devices. In addition, routing is partially combined with the channel allocation. This is because, for ZigBee devices whose interference avoidance is insufficient only with the channel allocation, the interference is avoided by updating packet forwarding routes at the ZigBee devices. Moreover, cooperation of the channel allocation with interference avoidance in time domain is more difficult under the assumption that Wi-Fi networks are not cooperative to the ZigBee network as considered in this paper. This is because Wi-Fi networks
do not process cooperative collision avoidance mechanism like stopping Wi-Fi communication for a certain time period as proposed in [30]. Thus, this paper focuses on joint channel allocation and routing. This approach corresponds to interference avoidance in both frequency and space domains. Computational load at each ZigBee device is suppressed by changing packet forwarding routes partially. Although some related works study interference avoidance in frequency and space domains by focusing on Wireless Sensor Network (WSN) [33], [34] and wireless mesh network [35], radio interference from Wi-Fi networks is not assumed.

The rest of this paper is composed as follows. Section 2 describes related works. Next, in Sect. 3, the system model (e.g., network model and channel utilization) and the proposed method are described in detail. Then, in Sect. 4, we evaluate the performance of the proposed method by computer simulation and confirm the effectiveness. Finally, Sect. 5 concludes this paper.

2. Related Works

2.1 Radio Interference Avoidance in Time Domain

S. Pollin et al. [17] experimentally prove that Wi-Fi Stations (STAs) and Access Points (APs) do not stop to wait for a backoff time even when a ZigBee device emits radio wave strongly. Hence, X. Zhang et al. [18] introduce signaler, which sends a stronger signal than ZigBee devices as soon as it detects ZigBee communication. This makes it easy for Wi-Fi STAs and APs to detect ZigBee signals. Similar approaches with signaler are introduced in [19] and mathematically analyzed in [20]. Queue-size based Busy Tone (QBT) [21] applies the approach with signaler to multi-hop ZigBee network, and implements it on n embedded platform. However, because non data communication uses a channel, the utilization efficiency of ZigBee channels is reduced.

J. Huang et al. [22] try to transmit ZigBee packets while a Wi-Fi STA or AP is not sending data. This duration is called white space. Each ZigBee device predicts the length of white space in Wi-Fi traffic, and adapts ZigBee packet size so that the packet transmission does not overlap with Wi-Fi traffic.

B. Lu et al. [23] build a channel idle state prediction model with logistic regression. This model is used to determine whether ZigBee packets should be transmitted or not.

J. W. Chong et al. [24] propose to estimate Wi-Fi traffic at the Wi-Fi side. Each Wi-Fi AP estimates the number of active STAs, and informs a ZigBee sink of its estimation. The sink informs ZigBee devices of the estimation, and each of the ZigBee devices decides whether it sends a data packet or not.

However, because ZigBee packet transmissions concentrate on specific durations, collisions among the ZigBee packets increase. Thus, it becomes more difficult to avoid interference from Wi-Fi as the amount of ZigBee data traffic is increased in near future.

2.2 Radio Interference Avoidance in Frequency Domain

M. S. Kang et al. [25] assume cluster tree topology in ZigBee network. In this method, each Cluster Head (CH) switches its channel if an ACK from a destination device is not replied after a defined number of consecutive attempts. Then, a new channel is selected at pseudo random. However, pseudo random selection cannot minimize packet loss because it just averages the packet loss incurred on each channel. For packet loss minimization, each ZigBee device should switch to a more appropriate channel.

S. Pollin et al. [26] propose to select a channel that minimizes the impact of Wi-Fi interference. Each ZigBee device overhears the current channel and the frequency that are expected to have minimal interference based on a Q-learning algorithm, and selects an appropriate channel. When ZigBee devices form a cluster tree topology, the number of receiving channels per device is more than two, and time division scheduling is needed.

R. M.-Elefteri et al. [27] propose to select an appropriate channel based on Received Signal Strength Indicator (RSSI). Each ZigBee device samples the RSSI on all the channels and informs their sink of its result. The sink selects the appropriate channel with the lowest number of RSSI samples based on the report from the ZigBee devices. Then, the sink sends a channel switch message to the ZigBee devices, and the ZigBee devices switch to the appropriate channel.

L. Tytgat et al. [28] focus on mesh topology. Each ZigBee device scans the channel on which the ZigBee device operates periodically and updates the information of interference power on the channel. Each ZigBee device switches its operating channel if another channel is preferable to the current channel.

CoHop [29] selects appropriate ZigBee channels even from channels adjacent to a busy channel by Wi-Fi interference, based on the insight that adjacent channels of such a busy ZigBee channel can have better quality even if all the channels overlap with the corresponding Wi-Fi channel because of the non-uniform spectrum power density of the Wi-Fi interference.

Controlling both ZigBee and Wi-Fi channels is also proposed [30]. In this method, an operating ZigBee channel is switched to a more appropriate channel when the interference from Wi-Fi affects the sink arrival rate of ZigBee packets. In addition, ZigBee device avoids interference from the Wi-Fi network by requesting the Wi-Fi network to stop the use of a specific channel for a certain time period. This method assumes that Wi-Fi networks are cooperative with ZigBee devices. Hence, this method is effective only in such limited environments.

Controlling only operating channels consumes channel resources when the amount of data traffic is increased as assumed in near future, because more ZigBee devices switch to not crowded channels. Thus, interference between ZigBee and Wi-Fi needs to be more alleviated also in
another domain besides frequency.

2.3 Radio Interference Avoidance in Space Domain

In order to avoid radio interference in space domain, many routing methods are proposed.

K.-H. Phung et al. [31] propose for all ZigBee devices to have two forwarding devices for backup.

J.-Y. Teo et al. [32] express radio interference relationship between ZigBee devices with conflict graph [36], and propose a new metric that is a overall degree of radio interferences for all the paths. With this metric, multiple packet forwarding routes are derived so that the metric is minimized. However, the calculation amount at each ZigBee device is increased to manage conflict graph and the metric.

2.4 Radio Interference Avoidance in Frequency and Space Domains

Some studies try to avoid radio interference both in frequency and space domains. J. Li et al. [33] study optimal routing problem with scheduling, channel, and transmission power assignment in WSN. Moreover, the authors design efficient heuristic algorithm based on random-walk which works well on large-scale WSNs. Aljuaij et al. [35] propose a method of the optimal configurations of routing, power control, and rate adaptation in wireless mesh network. Also, the authors develop approximations that compute nearly optimal solutions for scalability. However, these methods are too complex to be applied in practical ZigBee devices unless they simplify the methods [34]. It is also assumed that devices have multiple transceivers, which is expensive for ZigBee devices. Moreover, radio interference from other wireless networks than WSNs is not taken into account.

M. Barcelo et al. [34] propose joint routing, channel allocation, and power control method for real-life WSNs. The WSNs can select minimum energy consumption or maximum packet delivery ratio strategy as routing. Moreover, each device uses the channel that is least used by other devices as reception channel. On the other hand, transmission channel depends on parent’s reception channel. However, also in this method, radio interference from other wireless networks than WSNs is not considered.

2.5 Radio Interference Avoidance in Wireless Networks Other than WSNs Based on ZigBee

Many other works study radio interference management and avoidance. Some of them focus on Device-to-Device (D2D) networks underlaying cellular networks.

I. O. Sanusi et al. [37] decide groups of D2D devices and cellular users that use a common communication resource for spectrum efficiency with a deferred acceptance algorithm. Then, transmission power is allocated to D2D devices and cellular users to maximize the overall throughput of the system composed of a cellular network and underlaid D2D networks.

B. Gu et al. [38] apply double deep Q-network to solve a joint problem of communication resource and power allocation for D2D devices underlaying cellular networks. The objective is to maximize the total spectrum efficiency of all D2D devices. One advantage of this method is that no instantaneous channel state information is required. On the other hand, centralized approach like [37] requires latest channel state information.

I. Budhiraja et al. [39] propose communication resource and power allocation control based on deep reinforcement learning. Communication resource and transmission power are allocated to each D2D device so that minimum acceptable Signal-to-Interference and Noise Ratio (SINR) is kept for D2D devices and cellular users while mitigating interference among them. This control aims at not only maximizing total data rate at D2D devices but also assuring its fairness among D2D devices.

Y. Ren et al. [40] apply D2D communication underlaying a cellular network to Vehicle-to-Vehicle (V2V) connection, and propose grouping, channel allocation and transmission power control schemes to maximize the sum rate and the minimally achievable rate of all V2V the communication links.

X. Zhang et al. [41] apply deep reinforcement learning to V2V communication and Vehicle-to-Infrastructure (V2I) communication to find optimal allocation of communication resource and transmission power to vehicles in addition to selection of V2V communication or V2I communication.

These works [37]–[41] incorporate power control into their proposed methods, and assume D2D communication underlaying cellular networks. On the other hand, this paper focuses on not power control but channel allocation and routing. In addition, this paper considers ZigBee networks that suffer radio interference from Wi-Fi networks, which also differs from the works.

H.-B. Jeon et al. [42] study to apply full-duplex operation to D2D communication, in addition to resource allocation. A full-duplex function is applied to a limited number of devices due to the limitations of devices’ cost and complexity, and the devices with the full-duplex function are selected based on the centrality concept of graph theory. After that, communication resources are allocated to devices to limit the range of frequency used to the D2D network. On the other hand, in this paper, full-duplex operation is not considered and each ZigBee device is assumed to equip only a half-duplex function.

Some other works deal with interference management among Wireless Body Area Networks (WBANs). Interference reduction channel access mechanism (IR-CAM) [43] adjusts contention window size and frame length to avoid radio interference inside a WBAN and between WBANs.

J. Mu et al. [44] propose a channel allocation scheme to WBANs to avoid interference among them. The channel allocation is realized by k-means clustering and vertex
coloring algorithm based on the WBANs' locations and the distances among the WBANs.

These works [43], [44] assume radio interference among WBANs deployed in a small area, and consider interference avoidance only in time domain [43] or frequency domain [44]. On the other hand, this paper consider control in frequency and space domains in ZigBee networks that suffer radio interference from Wi-Fi networks.

3. Proposed Method

Related works explained in Sects. 2.1 to 2.3 focus on radio interference avoidance in only one of time, frequency, and space domains. On the other hand, this paper proposes joint channel allocation and routing in frequency and space domains. Compared with the related works in Sect. 2.4, this paper considers that ZigBee networks suffer radio interference from Wi-Fi networks. In addition, to suppress computational load at each ZigBee device, packet forwarding routes are changed only at ZigBee devices whose interference avoidance is insufficient by channel allocation control. Moreover, only one transceiver is required for ZigBee devices except for sinks. These designs of the partial route modification and the single-transceiver implementation are targeted for not increasing the computational load at each ZigBee device qualitatively. On the other hand, quantitative evaluation about the computational load is one of the future works, because this paper focuses on improving ZigBee packet loss, which is considered to be the most important problem, and quantitative evaluation of the computational load is the next challenge.

3.1 System Model

In the proposed method, we assume an environment where ZigBee and Wi-Fi systems are working in a same area. The ZigBee network faces radio interference from the Wi-Fi networks, and the Wi-Fi networks are not cooperative to the ZigBee network under assumption that the operators are different between the ZigBee and Wi-Fi systems. A typical application of the proposed ZigBee networks is to monitor environmental data like temperature, humidity, pollution level, illuminance, and so on, for smart home. Such measured data are used to control air conditioner, exhaust fan, illumination, and so on, in a home. Generally, in many of homes, Wi-Fi networks are installed, and ZigBee networks faces radio interference from Wi-Fi networks installed in the same home, other neighbor homes, and neighbor rooms in the case of condominium building. Figure 1 shows an example of the assumed environment.

Both of the ZigBee and Wi-Fi networks use the 2.4 GHz band channels. Figures 2 and 3 show each of channels that are used in the coexisting ZigBee and Wi-Fi networks. The ZigBee network uses ZigBee channels 11–14, 16–19, and 21–24, and the Wi-Fi networks use Wi-Fi channels 1, 6, and 11. We assume that the ZigBee network does not use ZigBee channels 15, 20, 25, or 26, for simplicity.

The ZigBee network forms a routing tree to forward data packets, generated at the ZigBee devices, to the sink. The tree is composed of some sub-trees each of which has the ZigBee device, directly connected to the sink, as the root. We assume that a common ZigBee channel is used by the ZigBee devices belonging to each sub-tree. In each sub-tree, there exist the paths from the root ZigBee device to the leaf ZigBee devices. Figure 4 shows an example of the tree topology, ZigBee channel usage at each sub-tree whose color shows its ZigBee channel, and the relationship between sub-tree and path. The channel usage means which ID of the channel each sub-tree uses. The channel ID, like channels 11, 12, is explained in the second paragraph of Sect. 3.1 and in Fig. 2.
3.2 Control Objective

In the proposed method, when the radio interference degrades the communication quality, the ZigBee channel used in the sub-tree is changed. In addition, if the communication quality is not improved enough, some ZigBee devices in the sub-tree switch to another channel, and the packet forwarding routes of the ZigBee devices are reconstructed so that they can forward data packets by the cooperation of neighbor ZigBee devices operating on the new ZigBee channel.

Figures 5 and 6 show examples where interference cannot be avoided only by ZigBee channel switching and where the interference can be avoided by reconstructing the routes to forward data packets in addition to ZigBee channel switching by the proposed method. Each color stands for a Wi-Fi channel and the four ZigBee channels overlapping with the Wi-Fi channel in the frequency domain. Some ZigBee devices belonging to the sub-tree operating on the green ZigBee channel in Fig. 5 cannot avoid the interference from one of the Wi-Fi networks only by switching the ZigBee channel because the sub-tree suffers the interference from the Wi-Fi networks on any ZigBee channels. In this situation, the proposed method works effectively (see Fig. 6). Specifically, the green sub-tree in Fig. 5 can avoid the interference from all the Wi-Fi networks by switching to the red ZigBee channel and reconstructing the packet forwarding routes for the three ZigBee devices indicated by star in Fig. 6. These three ZigBee devices reconstruct a new route to the blue sub-tree and switch to the blue ZigBee channel. Finally, all the sub-trees and ZigBee devices can avoid interference from all the Wi-Fi networks.

3.3 Collecting Channel Congestion Situation at the ZigBee Devices

Each ZigBee device collects the congestion situation on each ZigBee channel. The situation is notified to the sink, and used for the sink to decide the optimal ZigBee channel for each sub-tree and ZigBee devices whose packet forwarding routes should be reconstructed for radio interference avoidance.

Let $Z^n$ denote the set of ZigBee channel $z_n$, where $n$ is the channel ID shown in Fig. 2.

Each ZigBee device with ID $d$ overhears each of the ZigBee channels, and measures channel time occupancy $O_d^n$ as the ratio of “the duration during which the RSSI detected on ZigBee channel $z_n$ is carrier sense threshold (CST) or larger” to “a predefined period $P_c$”.

Then, this $O_d^n$ is added to the header of a data packet and notified to the sink so that the sink can find a channel with less interference for the sub-tree. The ID $d$ of the ZigBee device and the number of hops $h$ from the sink to the ZigBee device are also notified to the sink in the same manner. These values are managed at the sink.

3.4 Selection of Optimal ZigBee Channel and ZigBee Devices for Route Reconstruction

The sink decides the optimal ZigBee channel for each sub-tree, and the ZigBee devices whose packet forwarding routes should be changed for interference avoidance from Wi-Fi networks. The flow of this process is shown in Fig. 7.

When the sink receives a data packet from a ZigBee device, if a period of $P_{update}$ has been passed from the last decision, the sink decides the optimal ZigBee channel for each sub-tree as explained in the following paragraph.
First, for each ZigBee device $d$, the set of the ZigBee channels whose channel time occupancy does not exceed a threshold $O_{th}$ is collected. This set of the ZigBee channels \( \{ z_n \in Z \mid O_n^d \leq O_{th} \} \) is called device-worthy channel set. Here, $O_{th}$ is defined with the target packet arrival ratio $R_{TA}$ to the sink and the number of hops $h$ to the sink as

\[
O_{th} = \sqrt{1 - R_{TA}}. \tag{1}
\]

Next, for each path $p$ from the root ZigBee device to each of the leaf ZigBee devices, less adequate channels are deleted from the device-worthy channel sets at ZigBee devices on the path. Note that the relationship between sub-tree and path has been explained in Fig. 4. Finally, path-worthy channel set $C^p$, the set of channels appropriate to be used by the path $p$, is collected. Let $C^p_h$ denote the channel set at the $h$th hop ZigBee device $d^p_h$ from the root in the path $p$. This process is formally described as follows,

\[
D^p_h = C^p_{h-1} \setminus \{ z_n \in Z \mid O_n^d_h > O_{th} \} \tag{2}
\]

\[
C^p_h = \begin{cases} 
D^p_h & (D^p_h \neq \phi) \\
C^p_{h-1} & (D^p_h = \phi). 
\end{cases} \tag{3}
\]

Note that $C^p_1$ is the device worthy channel set at the root ZigBee device in the path $p$ as an initial set. Here, $D^p_h = \phi$ means that the ZigBee device $d^p_h$ has no adequate channel. Such ZigBee devices are regarded as ZigBee devices whose packet forwarding routes should be reconstructed as explained later. Finally, the leaf ZigBee device, which is the $h$th hop from the root decides the channel set $C^p_h$ as the path-worthy channel set $C^p$ for the path $p$.

This process to obtain path-worthy channel set $C^p$ is repeated for all the paths to all the leaf ZigBee nodes in the sub-tree. Let $N_p$ denote the number of paths in the sub-tree. Then, the optimal channel set $C^T$, for the sub-tree $T$ is derived as the union of the path-worthy channel sets of all the paths in the sub-tree as

\[
C^T = \bigcup_{p=1}^{N_p} C^p. \tag{4}
\]

After deriving $C^T$, for each channel $z_n$ in $C^T$, the number of rerouting devices is calculated as follows. A rerouting device is a candidate whose packet forwarding route is reconstructed to avoid interference.

For each path $p$ from the root ZigBee device to each of the leaf ZigBee devices in the sub-tree, it is checked whether the channel time occupancy $O_n^d$ at the $h$th hop ZigBee device $d^p_h$ is larger than $O_{th}$. If $O_n^d$ is larger than $O_{th}$, the ZigBee device $d^p_h$ and all the descendant ZigBee devices are selected as rerouting devices for the channel $z_n$. This process is repeated for all channels in $C^T$.

Finally, the channel with the smallest number of rerouting devices in $C^T$ is adopted as the optimal ZigBee channel for the sub-tree.

3.5 Switching to the Optimal ZigBee Channel and Reconstructing Packet Forwarding Routes

The optimal ZigBee channel and rerouting devices for the channel, decided in Sect. 3.4, are notified to all the ZigBee devices in the sub-tree. If at least one ZigBee device in a sub-tree detects successive packet losses, all the ZigBee devices in the sub-tree switch the operating channel to the optimal ZigBee channel. Then, packet forwarding routes for rerouting ZigBee devices in the sub-tree are also changed. The flow of this process is shown in Fig. 8.

Specifically, first, when a ZigBee device detects $N$ successive packet losses, it switches the operation channel to the optimal channel after broadcasting a message to inform neighbor ZigBee devices in the sub-tree of the channel switching. Neighbor ZigBee devices that received the message also rebroadcast the message and switch their operation channel to the optimal channel.

Then, ZigBee devices, which were informed of being decided as rerouting devices from the sink, reconstruct their packet forwarding routes, as follows. On the ZigBee channel $z_n$ whose channel time occupancy $O_n^d$ at a rerouting ZigBee device is minimum, the device broadcasts a Reroute Request (ReREQ) message. If a neighbor ZigBee device receives this ReREQ message, it replies with a Route Reply (RREP) message. Then, if the rerouting ZigBee device receives this RREP message, it sends a RREP Acknowledge (ACK) message to the neighbor ZigBee device, and reconstructs its packet forwarding route by setting the neighbor ZigBee device as the next hop device to the sink.

On the other hand, if the rerouting ZigBee device cannot find such a next hop device by failing to receive a RREP ACK message on the ZigBee channel with minimum channel time occupancy, the above route reconstruction process is repeated on other ZigBee channels with the ascending order of the channel time occupancy at the rerouting ZigBee device until such a next hop device is found. Here, if such a next hop device cannot be found on all the ZigBee channels, the rerouting ZigBee device does not reconstruct its packet forwarding route and switches to the optimal channel.
notified from the sink.

4. Performance Evaluation

The performance of the proposed methods was evaluated by computer simulation with QualNet 7.1 [45].

4.1 Simulation Model

Figure 9 shows the ZigBee network used in this simulation. A 27-meter-square area was divided into 81 3-meter-square cells. One ZigBee device was deployed randomly in each cell. The location of the sink was fixed at the center of the area. Each ZigBee device sent packets with the size of 60 Byte to the sink every 60 s. The communication range and channel transmission rate of each ZigBee device were 10.3 m and 250 kbps, respectively. In the proposed method, the minimum time interval for updating optimal ZigBee channels $P_{update}$ was set to 60 s, and parameter $RTA$ was set to 0.5. The number of successive packet losses $N$ to trigger ZigBee channel switching was set to 5.

Four Wi-Fi networks (Wi-Fi 1, 2, 3, 4), each of which consists of one AP and one STA, were deployed between two circles whose centers are the sink and radiuses are 100 m and 130 m, respectively (see Fig. 10). It assumes an environment where ZigBee devices suffer from Wi-Fi APs and Wi-Fi APs are not disturbed by ZigBee devices at all. Wi-Fi 1, 2, 3, and 4 used Wi-Fi channel 1, 5, 9, and 13, each of which interferes with ZigBee channels 11-14, 15-18, 19-22, and 23-26, respectively. Packet flows arrived at each Wi-Fi AP according to Poisson arrival process whose average rate was $\lambda$ [bps], and once a flow arrived, 1000 Byte packets were generated every 2 ms for 600 s. The communication range and channel transmission rate of Wi-Fi were 108.7 m and 11 Mbps, respectively.

Each simulation duration was 30,000 s and we evaluated ZigBee packet arrival ratio calculated as the ratio of ZigBee packets that arrived at the sink to all the ZigBee packets generated at the ZigBee devices. The proposed method that adaptively switches both ZigBee channels and packet forwarding routes denoted as “Proposal w/ rerouting” was compared with the partial proposed method, denoted as “Proposal w/o rerouting”, where only ZigBee channel switching was processed, and the static method where both ZigBee channels and packet forwarding routes were not updated. No related works combine such partial route modification, only at ZigBee devices whose interference avoidance is insufficient, with ZigBee channel allocation control, under the assumption that Wi-Fi networks are not cooperative to the ZigBee network. In addition, the most important evaluations include quantitative evaluations about how the proposed partial route modification and the proposed channel allocation contribute to the improvement of the ZigBee packet arrival ratio. Hence, the proposed method was compared to the partial proposed method with only channel switching and the static method without the proposed channel allocation control and the proposed partial route modification as representative simplified cases.

4.2 Simulation Results in a Strategic ZigBee Channel Deployment

First, with the initial ZigBee channel deployment and route settings in the ZigBee network described in Fig. 11, each simulation was run. In Fig. 11, each color of the sub-trees means a different ZigBee channel. Eight ZigBee channels
were used in total, and this deployment means a case that a strategic initial channel deployment for avoiding interference among ZigBee sub-trees is possible.

Figure 12 shows the ZigBee packet arrival ratio as a function of the average arrival rate $\lambda$ of Wi-Fi flows.

The partial proposed method (Proposal w/o rerouting) increases the ZigBee packet arrival ratio compared with the static method. Moreover, in the proposed method (Proposal w/ rerouting), the ZigBee packet arrival ratio is further improved. These results mean that the switching of ZigBee channels contributes to interference avoidance to some extent, and the cooperation of ZigBee channel switching and reconstructing some packet forwarding routes can avoid radio interference from Wi-Fi more effectively.

4.3 Simulation Results without a Strategic ZigBee Channel Deployment

Then, to evaluate the robustness to initial ZigBee channel deployment, the performance was evaluated in a case that a strategic ZigBee channel deployment is insufficient. Specifically, only four ZigBee channels are initially used as described in Fig. 13, where each color of the sub-trees means a different ZigBee channel as in Fig. 11.

Figure 14 shows the ZigBee packet arrival ratio in this nonstrategic ZigBee channel deployment. The horizontal axis shows the average arrival rate $\lambda$ of Wi-Fi flows, and the vertical axis is the ZigBee packet arrival ratio.

Compared with the results in Fig. 12, the static method seriously decreases the ZigBee packet arrival ratio because both ZigBee channels and packet forwarding routes cannot be changed during the operation and the inadequacy of the initial ZigBee channel deployment affects the performance reduction. On the other hand, from the results of the proposed method (Proposal w/ rerouting) and the partial proposed method (Proposal w/o rerouting), the reduction of the ZigBee packet arrival ratio is suppressed minimally by adaptively changing ZigBee channels and packet forwarding routes to avoid radio interference from Wi-Fi networks.

5. Conclusion

In this paper, we proposed joint channel allocation and routing for ZigBee networks to avoid radio interference suffered from Wi-Fi networks. The proposed methods avoid interference in both frequency and space domains by updating optimal ZigBee channel for each ZigBee sub-tree and reconstructing packet forwarding routes at some limited ZigBee devices whose interference avoidance is insufficient only by the channel updating control.

Through the performance evaluation, we confirmed the effectiveness of the proposed methods, indicating that ZigBee packet arrival ratio to sink is improved in both initial ZigBee channel deployments, one is a case that ZigBee channels are deployed strategically for interference avoidance among ZigBee sub-trees and the other case is that such strategical deployment is impossible.

Future works include further performance improvement of ZigBee packet arrival ratio by expanding the process to reconstruct packet forwarding routes.

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