PAPER

A ZigBee/Wi-Fi Cooperative Channel Control Method and Its Prototyping

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SUMMARY Coexistence between ZigBee and Wi-Fi technologies, which operate within the same frequency band, is increasing with the widespread use of the IoT (Internet of Things). ZigBee devices suffer significant decreases in the sink arrival rate of packets in the presence of Wi-Fi interference. To overcome this problem, many channel control methods have been proposed. These methods switch only ZigBee channels to avoid interference with Wi-Fi. In contrast, we propose a cooperative channel control method for improving ZigBee packet arrival rate by controlling both the Wi-Fi and ZigBee channels. Specifically, the proposed method not only controls ZigBee devices and channels but also requests a temporary pause in the use of specific Wi-Fi channels. Finally, computer simulations show the effectiveness of the proposed method from the viewpoints of ZigBee's packet arrival rate and applications' satisfaction. In addition, the feasibility of the proposed method is also confirmed by experiments with prototyping.

key words: *ZigBee, Wi-Fi, channel control*

1. Introduction

Recently, more and more devices, such as cars and home appliances, automatically communicate with other wireless devices and control themselves, creating what is called the IoT (Internet of Things) [1]–[5]. In the IoT, ZigBee [6] is used in many environments to improve the sensitivity and reduce the cost of wireless devices. On the other hand, Wi-Fi [7] is also used very widely. Therefore, coexistence between ZigBee and Wi-Fi, both of whose communication take place in the 2.4 GHz band, is increasing [8].

In such environments, ZigBee devices suffer severe packet loss when interference occurs, mainly because the transmission power of Wi-Fi is much higher than that of ZigBee [9]–[12].

Interference can be avoided in one of the following domains; time, frequency, or space. Interference avoidance in the space domain is difficult for our target IoT services, in which numerous wireless devices are deployed. Interference avoidance in the time domain has already been studied. S. Pollin et al. [9] experimentally prove that Wi-Fi does not stop and wait for a backoff time even when ZigBee devices emit radio wave strongly. Hence, [13] uses *Signaler*, which transmits a stronger signal than the ZigBee devices as soon as it detects ZigBee communication. This makes it easy for Wi-Fi to detect ZigBee signals. However, because non data communication radio uses a channel, the utilization efficiency of the frequency deteriorates. In [14], RTS/CTS handshake is used from ZigBee to pause Wi-Fi communication temporarily. When a ZigBee device transmits a packet, an RTS is transmitted from a controller in the ZigBee network. This RTS is received by a helper AP (Access Point), then the AP transmits a CTS. During the period specified in the RTS and CTS, ZigBee devices can transfer packets. However, this method needs additional ZigBee devices; a controller and helper APs. In [10], ZigBee devices transmit data in periods when Wi-Fi devices are not transmitting data. This period is called *white space*. The ZigBee devices predict the length of the *white space* in Wi-Fi traffic, and adapt frame size in order not to collide with Wi-Fi transmissions. However, because the amount of ZigBee transmissions is intensively increased in *white space* periods, collisions among ZigBee devices may increase. In addition, it is unrealistic to achieve time division scheduling on all devices. Therefore, time domain interference avoidance cannot be applied to a large percentage of ZigBee traffic.

Hence, we study interference avoidance in the frequency domain. In existing works focusing on the frequency domain, only ZigBee devices switch their operating channels to avoid interference with Wi-Fi [15]–[19]. However, switching the channels of both ZigBee and Wi-Fi signals is expected to lead to more efficient use of the channels and improvement in the sink arrival rate of ZigBee packets. Therefore, we propose a cooperative channel control method for both ZigBee and Wi-Fi in coexistence spaces. This methodology would be used by both Wi-Fi users and ZigBee applications in parallel. The main idea of the proposed method is cooperative channel changing based on the required packet receiving rate for each service [20]. This paper is its extended version.

In the proposed method, ZigBee devices avoid interference with Wi-Fi by requesting Wi-Fi to stop using a specific channel for a certain time period. In addition, the ZigBee channel is switched to a more appropriate channel whenever the interference from Wi-Fi affects the arrival rate of the ZigBee packets. We limit the length of the Wi-Fi channel pause to minimize the decrease in Wi-Fi throughput.

The remainder of this paper is organized as follows. In

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Sect. 2, we discuss related works that consider the coexistence of ZigBee and Wi-Fi. Section 3 explains our proposed method. In Sect. 4, we evaluate the proposed method by simulation experiments and prototyping. Finally, we conclude this paper in Sect. 5.

2. Related Work

Wi-Fi interference causes severe collisions and packet losses for ZigBee devices when ZigBee and Wi-Fi devices use the same frequency band. To overcome this problem, many methods have been proposed. We focus on interference avoidance methods in the frequency domain.

In [15], each CH (Cluster Head) of a cluster communicates with the BRD (BRiDge) of the next cluster. The CH switches its channel if ACK (ACKnowledgement) 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, ZigBee devices should switch to a more appropriate channel.

In [16], each ZigBee device selects a channel that minimizes the impact of Wi-Fi interference. Each ZigBee device overhears the current channel and the frequency that is expected to have minimal interference based on a Q-learning algorithm, and selects an appropriate channel. If another (i.e., not the current) channel will have less impact from interference, each ZigBee device switches to the channel.

In [17], each ZigBee device samples the RSSI (Received Signal Strength Indicator) of all ZigBee channels and informs the sink of its result. The sink selects the appropriate channel with the lowest number of RSSI samples based on the report of the ZigBee devices that belong to the sub-tree, whose root is the sink. The sink sends a channel switch message to the ZigBee devices, and the ZigBee devices switch to the appropriate channel.

Tytgat et al. [18] focus on a mesh network. Each ZigBee device scans a channel which the ZigBee device operates on periodically and updates the information on interference power of the channel. The ZigBee device switches its channel if another channel is preferable to the current channel.

In [19], the Wi-Fi AP estimates the number of active STAs and informs a sink of its estimation. The sink informs ZigBee devices of its estimation, and the ZigBee devices decide whether they send data or not.

In these existing works, however, only ZigBee devices switch their operating channels to avoid interference with Wi-Fi. Controlling only ZigBee channels will lack the channel capacity for ZigBee devices when additional ZigBee devices generate a greater amount of data in the future.

3. Proposed Method

The proposed method not only controls ZigBee channels but also requests a temporary pause in the use of specific Wi-Fi channels, based on traffic load and external interference in ZigBee networks.

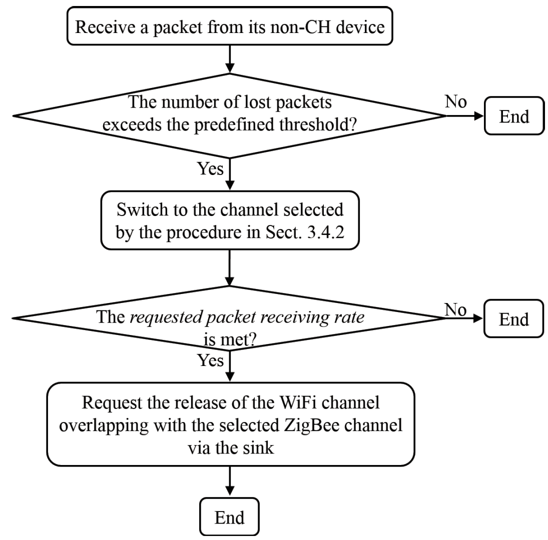


Fig. 1 Channel switching control in intra-cluster communications.

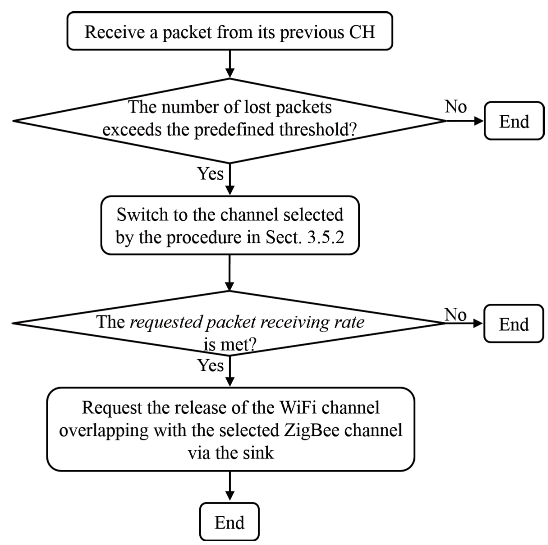


Fig. 2 Channel switching control in inter-cluster communications.

The proposed method is divided into the channel switching control in intra-cluster communications and inter-cluster communications. Figures 1 and 2 show the flowchart of these controls, respectively. They are alternately invoked at constant time interval.

3.1 System Model

Figure 3 shows an environment where Wi-Fi and ZigBee communication is occurring in the same area. We assume that the owner of Wi-Fi APs and that of ZigBee devices are cooperative. In a typical case, they are the same.

Figure 4 shows the arrangement of the ZigBee and Wi-Fi channels on the 2.4 GHz frequency band. All ZigBee devices periodically generate and transmit packets to a sink. A Wi-Fi AP (Access Point), which can use three non-

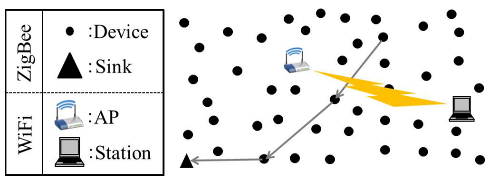


Fig. 3 Coexistence of ZigBee and Wi-Fi.

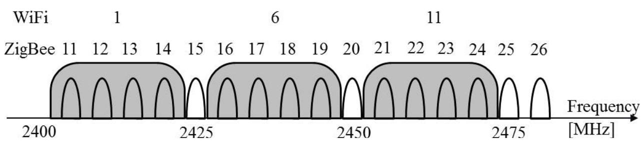


Fig. 4 Channels used by ZigBee and Wi-Fi.

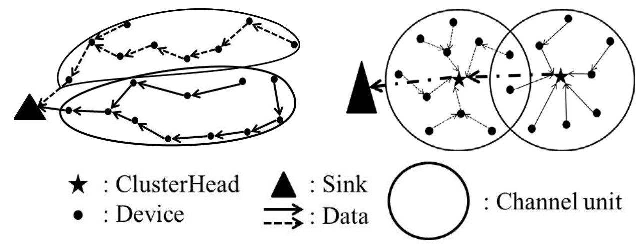
overlapping Wi-Fi channels at the same time, sends data packets to Wi-Fi STAs. Both ZigBee and Wi-Fi networks use the 2.4 GHz band. ZigBee uses channels 11–14, 16–19, and 21–24, and Wi-Fi uses channels 1, 6, and 11. We assume that ZigBee devices do not use channels 15, 20, 25, or 26 for simplicity. Moreover, Wi-Fi cooperates with ZigBee, and the Wi-Fi AP and the ZigBee sink communicate with each other through a backbone network.

3.2 Assumed Network Topology and Channel Usage

Wireless links between specific ZigBee devices, like between non-CH devices and their CH device, must use the same channel when such devices transfer packets. We call these wireless links the "*channel unit*" in a ZigBee network. In conventional cluster tree topology, a *channel unit* is a subtree whose root is the sink. In contrast, we focus on clustering, where each intra-cluster communication and inter-cluster communication is a *channel unit*. Figure 5 shows an example of channel units. Intra-cluster and inter-cluster communications are performed using a TDMA method. Thus, only a CH and its child devices use the same channel. With a ZigBee beacon, time synchronization among the devices is achieved. Data packets generated by non-CH devices are sent to their parent CH via single or multi-hop communications, then transferred to the sink through its inter-cluster communications. Note that the proposed method is independent of clustering algorithms and we do not assume a specific one. If anything, HEED [21] can be applied to our proposed method.

3.3 Control Policy of ZigBee Channel Switching and Temporal Pause of Wi-Fi Channel

We define the *requested packet receiving rate* $a = p/q$ ($p \leq q$) as a criterion for the packet arrival rate that ZigBee applications request [22]. This is defined as follows. Any q packets with successive sequence numbers are considered to be one group. Here, if a group includes more than or equal to p packets received by its sink, the group is determined to be a satisfied group. Figure 6 shows an example



(a) Conventional cluster tree. (b) Clustering in the proposed method.

Fig. 5 Channel unit.

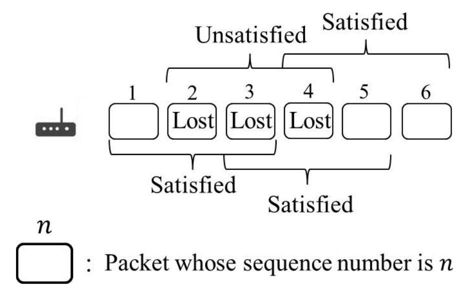


Fig. 6 *Example of requested packet receiving rate* ($p = 1$ and $q = 3$).

of $p = 1$ and $q = 3$. Any three packets with successive sequence numbers, like packet sequences 1–3, 2–4, and so on, are considered to be one group. Then, the sink counts the number of received packets for each group. When the number of received packets in a group is more than one, the *requested packet receiving rate* of this group is satisfied.

In the proposed method, ZigBee devices switch their operational channels when there is a possibility that the *requested packet receiving rate a* will not be satisfied due to interference. In addition, as the possibility increases, the sink requests the Wi-Fi network to temporarily pause the use of the Wi-Fi channels that overlap with the ZigBee device channels. Thus, the interferences among ZigBee *channel units* and between ZigBee and Wi-Fi are avoided. In our research, we call pausing the use of a Wi-Fi channel "*channel release*". The following subsections explain these specific controls by dividing them into intra-cluster and inter-cluster communications.

3.4 Channel Switching Control in Intra-Cluster Communications

In intra-cluster communications, each CH determines whether to switch the operational channel of its cluster and whether to request *channel release* to release the Wi-Fi channel overlapping with the channel to which the ZigBee devices are switching. These specific procedures are explained in Sects. 3.4.1 and 3.4.2. If a new channel to switch to is decided, the CH informs its child non-CHs of the new channel (see Fig. 7). In addition, if the *channel release* is decided, it is requested from the CH to the Wi-Fi AP via the ZigBee sink and the backbone network.

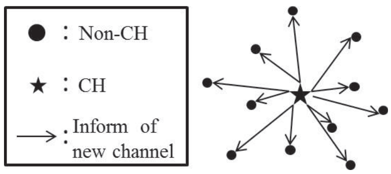


Fig. 7 The way of informing of a new channel (intra-cluster communication).

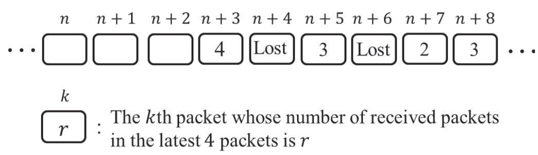


Fig. 8 Calculation of r ($p = 1$ and $q = 4$).

3.4.1 Switching ZigBee Channels and Requesting Channel Release to AP

Each CH calculates the number of received packets r in the latest q packets, when it receives a packet from one of the non-CH nodes. This r is added to the header of the packet; this header information is used for channel switching in inter-cluster communications (see Sect. 3.5). Figure 8 shows an example of calculating r when a CH receives packets whose *requested packet receiving rate* is 1/4. A threshold m is an integer where $0 \leq m < q - p$. When r satisfies

$$r \leq p + m, \quad (1)$$

the CH decides to change the current intra-cluster communication channel. Specifically, it informs non-CH nodes of the new channel that will be selected by the procedure described in Sect. 3.4.2 and switches the current channel to the selected channel. Because the *requested packet receiving rate* is not met if m more packets in the q packets drop, the channel is switched to improve performance. In other words, the threshold value m means a kind of margin to decide whether the interference is critical or not for satisfying the requested packet receiving rate a. Larger m leads to earlier channel change. It can be set by the user.

In addition, when r satisfies

$$r \leq p, \quad (2)$$

the CH requests *channel release* about the WiFi channel overlapping with the new ZigBee channel to the Wi-Fi AP.

3.4.2 Selecting the New ZigBee Channel

Each CH selects a new channel that will have the least impact from interference. RSSI is used as a measurement of the impact from interference because there is a substantial correlation between high RSSI values and increased packet loss [17].

Non-CHs which have no packets to send overhear other ZigBee channels $Z = \{z \mid z \in z_{11}–z_{14} \cup z_{16}–z_{19} \cup z_{21}–z_{24}\}$ in order until they generate a new packet to send. Here, z_n is the ZigBee channel n as shown in Fig. 4. Each non-CH informs its CH of the RSSI value of each ZigBee channel, detected by the overhearing process of ZigBee channels. After receiving such detected RSSI values from its non-CHs, each CH manages $S = \{s_z \mid z \in Z\}$ as the set of RSSI s_z that is the maximum value among the RSSI values for channel z. Finally, each CH selects a new channel that satisfies $\min\{s_z \mid z \in Z\}$.

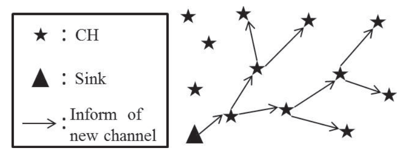


Fig. 9 The way of informing a new channel (inter-cluster communication).

3.5 Channel Switching Control in Inter-Cluster Communications

In Sect. 3.4, we discussed how a CH switches its ZigBee channel and requests *channel release* in intra-cluster communications. On the other hand, in inter-cluster communications, the sink selects a new channel to which ZigBee devices switch. The sink informs the CHs of the need to switch to a new channel (see Fig. 9). The method used to inform the Wi-Fi AP of a *channel release* request in inter-cluster communication is the same as that in intra-cluster communication.

3.5.1 Switching ZigBee Channels and Requesting Channel Release to AP

Unlike intra-cluster communications, each CH sends $2q - 1$ packets, buffered in itself, in descending order from r, which is included in a packet header as explained in Sect. 3.4.1, (i.e., from packets with lower priority from the viewpoint of the *requested packet receiving rate*) in order to investigate strength of the interference on the operating channel. Then, the next relay CH calculates the number of received packets r' of the latest q packets from the CH.

This r' is used to switch the ZigBee channel and request *channel release* in the same way as intra-cluster communication although r' is not added to the header.

The CH judges whether the interference on the operating channel is weak and sends packets in the ascending order of r (i.e., in order of higher importance from the viewpoint of the *requested packet receiving rate*) if the inter-cluster channel is not switched until the CH sends $2q - 1$ packets. On the other hand, when the channel for inter-cluster communication is switched, the CH sends $2q - 1$ packets in descending order of r (i.e., r is in inverse proportion to the interference).

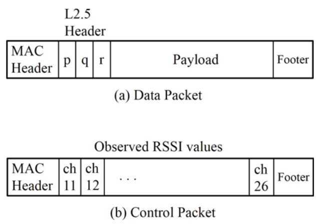


Fig. 10 Packet configuration.

3.5.2 Selecting the New Channel to Which ZigBee Devices Switch

Each CH calculates the sum S_z of s_z and informs the sink of the value. The sink selects the new channel by using S_z similar to the method by which s_z is used in intra-cluster communication.

3.6 Wi-Fi Channel Releases

Finally, this subsection explains the *channel release*. When a Wi-Fi AP receives a request for *channel release* from ZigBee devices, it pauses the use of the specific Wi-Fi channel that is about to overlap with the new ZigBee channel. The AP continues to pause the use of the Wi-Fi channel for a specified duration if the AP receives a *channel release* request for the same Wi-Fi channel, otherwise the AP resumes to use the Wi-Fi channel. The pause duration for the Wi-Fi channels is defined in advance.

3.7 Packet Configuration

To realize the proposed scheme, we introduce L2.5 header between MAC header and payload like a shim header in MPLS. A data packet carries a sensing data in its payload with parameters p, q and the number of received packets r in its L2.5 header as shown in Fig. 10(a). The L2.5 header contains a few bytes, so that it does not reduce the communication efficiency significantly.

In addition, the proposed scheme uses two types of control packet; for RSSI information gathering and for requesting channel release. A control packet uses a standard MAC command frame format defined in IEEE802.15.4. The type of control packet can be distinguished by *Command Frame ID*. A control packet for RSSI information gathering contains observed values as shown in Fig. 10(b). A control packet for requesting channel release has no payload (nothing to send).

4. Performance Evaluation

In this section, we conduct simulations in the environments described in Sect. 3.1 and shown in Fig. 3 in order to evaluate the performance of the proposed method.

4.1 Simulation Model

Figure 11 shows a ZigBee network topology in which five ZigBee applications transmit packets to a sink. A 5 [m] × 5 [m] square was divided into 25 1 [m] × 1 [m] grid tiles. One ZigBee device was deployed randomly in each of the 1 [m] × 1 [m] grids per application. The location of the sink was fixed at the bottom-left corner of the grid; locations of CHs were fixed at the grid points shown in Fig. 11. Each ZigBee device communicated with only devices providing the same application. An AP and three STAs communicating through Wi-Fi were deployed at locations where the ZigBee's radio signals did not reach (see Fig. 12).

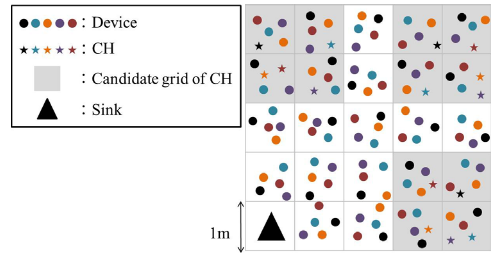


Fig. 11 ZigBee network topology.

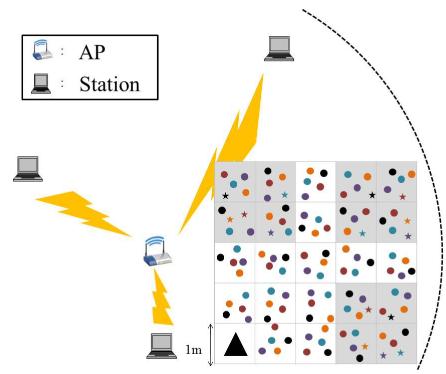


Fig. 12 Simulation environment.

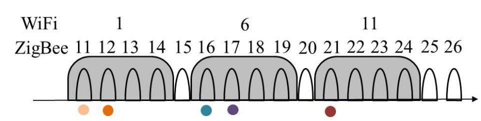


Fig. 13 Initial state.

Figure 13 shows the initial channel on which each ZigBee application device operates at the beginning of the simulation.

The simulation settings of the ZigBee devices were as follows.

- Data size: 120 [Byte]
- Data generation interval: t [s] period
- *Requested packet receiving rate*: 8/20

Table 1 shows the data generation interval t of each application.

The Wi-Fi conditions were set as follows. IEEE 802.11b was used and Wi-Fi communication was generated only from the AP to the STAs.

- Data size: 30 [MByte]

Table 1 Data generation interval of each application.

Application	Interval [s]
●	0.4
●	0.6
●	0.8
●	1.0
●	1.2

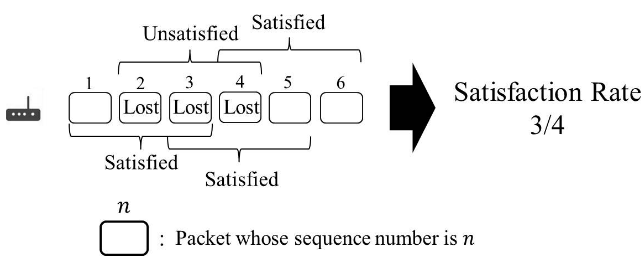
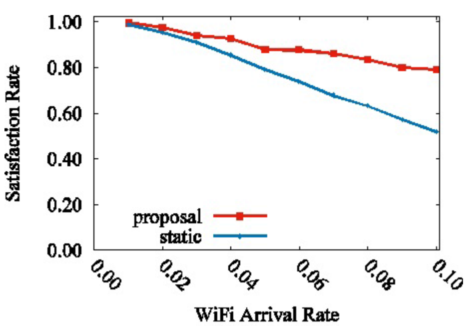
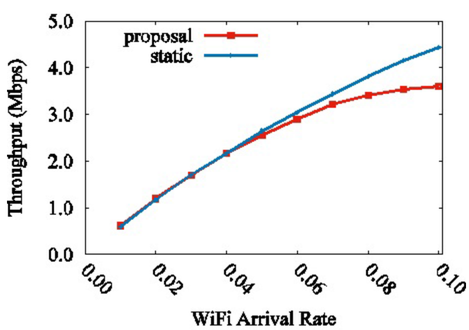


Fig. 14 An example of calculation when the *requested packet receiving rate* is 1/3.



(a) Satisfaction rate.



(b) Throughput.

Fig. 15 Evaluation Results.

- Data generation: Poisson arrival process whose average rate is λ [packets/s]

Finally, the simulation settings for the proposed method are shown as follows.

- Communication duration of intra-cluster/inter-cluster: every 1 [s]
- Pause duration of Wi-Fi: 5 [s/request]
- Threshold m: 5

Using QualNet 7.1 [23], we implemented the proposed method and compared it to a static method that never switched ZigBee channels, because no existing works consider cooperation between ZigBee channel switching and WiFi channel release.

Fig. 16 Implemented sink node and cluster head node.

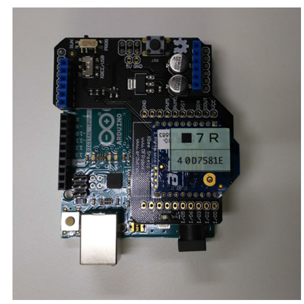


Fig. 17 Implemented sensor node.

We defined the *satisfaction rate* as a performance measure. This value indicates the ratio of the period of time when the *requested packet receiving rate* was satisfied to the whole simulation time. Specifically, the *satisfaction rate* of a flow is the ratio of the number of satisfied groups to all possible groups. Figure 14 is an example of the calculation when the *packet receiving rate* is 1/3.

In addition, we used throughput as a performance measure for Wi-Fi.

4.2 Simulation Results

Figure 15 shows the simulation results. The horizontal axis is λ, and the vertical axes of Fig. 15(a) and of Fig. 15(b) are the satisfaction rate of ZigBee devices and the Wi-Fi throughput, respectively.

The proposed method improves the *satisfaction rate* compared with the static method as the arrival rate of Wi-Fi increases as shown in Fig. 15(a). The satisfaction rate is due to avoidance of interference between ZigBee and Wi-Fi through stopping the use of a specific Wi-Fi channel and simplifying inter-cluster communication among ZigBee devices. In addition, the reduction in Wi-Fi throughput using the proposed method is less than 20% because ZigBee devices select specific Wi-Fi channels to pause in order not to permanently halt the use of a channel or traffic as a whole. In other words, the proposed method achieves higher ZigBee satisfaction rate by reasonable degradation of Wi-Fi throughput.

Table 2 Sink and cluster head.

model	RaspberryPi 2 ModelB BCM2836
CPU	ARM Cortex-A7 900 [MHz]
memory	1 [GB]
UART	57600 [bps]

Table 3 Sensor node.

model	Arduino UNO 2012 R3 Mega328
CPU	Atmel ATMega328P
UART	9600 [bps]

Table 4 ZigBee interface.

model	Digi XBee S2C ZigBee
Frequency Band	2.4 [GHz]
Data Rate	250 [Kbps]

```
18/11/26 10:49:51.977|pool-37-thread-1|ClusterHead
Service [Info]
SensingData from 0013A20040D75812. PANID:7,
Window is not full. Receive rate:1/7.
18/11/26 10:49:52.041|pool-37-thread-2|ClusterHead
Upstream [Info]
Submit SensingData to 0000000000000000 on
upstrem. d:7, PANID:6, NodeAddr:0013A20040D75822
18/11/26 10:49:52.067|pool-37-thread-1|ClusterHead
Service [Info]
SensingData from 0013A20040D75812. PANID:7,
Window is not full. Receive rate:2/7.

(skip)

18/11/26 10:49:52.439|pool-37-thread-1|ClusterHead
Service [Info]
SensingData from 0013A20040D75812. PANID:7,
Window is not full. Receive rate:6/7.
18/11/26 10:49:52.498|pool-37-thread-2|ClusterHead
Upstream [Info]
Submit SensingData to 0000000000000000 on
upstrem. d:7, PANID:6, NodeAddr:0013A20040D75829
18/11/26 10:49:52.531|pool-37-thread-1|ClusterHead
Service [Info]
SensingData from 0013A20040D75812. PANID:7,
Window is full. Receive rate:7/7.
18/11/26 10:49:52.594|pool-37-thread-2|ClusterHead
Upstream [Info]
Submit SensingData to 0000000000000000 on
upstrem. d:7, PANID:6, NodeAddr:0013A20040D7583A
18/11/26 10:49:52.635|pool-37-thread-1|ClusterHead
Service [Info]
SensingData from 0013A20040D75812. PANID:7,
Window is full. Receive rate:7/7.
```

Fig. 18 Experimental log in CH.

4.3 Prototyping

To confirm the feasibility of the proposed methods, we made a prototype system as follows.

We made 1 sink node (Fig. 16), 5 CH nodes (Fig. 16), and 20 sensor nodes (Fig. 17) with XBee interface. Their specifications are summarized in Tables 2, 3 and 4, respectively. In addition, we also made 3 Wi-Fi APs with the channel control function in cooparation with the sink node.

```
18/11/26 10:51:07.036|pool-37-thread-1|ClusterHead
Service [Info]
SensingData from 0013A20040D7583A.
Window is not full. Receive rate:3/7.
18/11/26 10:51:11.844|pool-37-thread-1|ClusterHead
Service [Info]
SensingData from 0013A20040D7583A.
Window is not full. Receive rate:4/7.
18/11/26 10:51:12.128|pool-37-thread-1|ClusterHead
Service [Info]
SensingData from 0013A20040D75822.
Window is not full. Receive rate:4/7.
18/11/26 10:51:12.638|pool-37-thread-1|ClusterHead
Service [Info]
SensingData from 0013A20040D7581C.
Window is not full. Receive rate:3/7.
18/11/26 10:51:16.848|pool-37-thread-1|ClusterHead
Service [Info]
SensingData from 0013A20040D7583A.
Window is not full. Receive rate:5/7.
18/11/26 10:51:16.929|pool-37-thread-1|ClusterHead
Service [Info]
SensingData from 0013A20040D75822.
Window is not full. Receive rate:5/7.
18/11/26 10:51:17.320|pool-37-thread-1|ClusterHead
Service [Info]
SensingData from 0013A20040D7581C.
Window is not full. Receive rate:4/7.
18/11/26 10:51:17.401|pool-37-thread-1|ClusterHead
Service [Info]
SensingData from 0013A20040D75829.
Window is not full. Receive rate:3/7.
```

Fig. 19 Packet drops recorded in CH.

```
18/11/26 10:51:32.582|pool-37-thread-1|ClusterHead
Service [Info]
d <= p. Planned suppressing WiFi conflicts
with Z_next[ZB12]
18/11/26 10:51:32.590|pool-37-thread-1|ClusterHead
Service [Info]
Submit WiFi suppression request conflicts
with Z_next[ZB12]
```

Fig. 20 Channel release request.

Each sensor node sends a packet to the sink node periodically. The parameters p and q in the proposed method were set to 4 and 7, respectively. Each Wi-Fi AP uses channel 1, 6, 11, respectively. In the initial setting, all channels used by ZigBee nodes are identical.

At first, Fig. 18 shows a log where ZigBee packets are transferred from the sensor nodes to the sink via CH nodes without the WiFi interference. This shows that all packets were successfully received by the CHs by changing the used channel in each cluster. Specifically, after the number of total received packets reached seven from the 19th line of the log, the receive rates are 7/7 (see 19th and 25th lines), which means all the latest seven packets were received.

Next, we started a heavy file tranfer on in a Wi-Fi net-

```
18/11/26 10:51:52.063|pool-37-thread-1|ClusterHead
Service [Info]
SensingData from 0013A20040D75812. PANID:7,
Window is not full. Receive rate:3/7.
18/11/26 10:51:52.071|pool-37-thread-2|ClusterHead
Upstream [Info]
Submit SensingData to 0000000000000000 on
upstrem. d:7, PANID:6, NodeAddr:0013A20040D7583A
18/11/26 10:51:52.078|pool-37-thread-1|ClusterHead
Service [Info]
SensingData from 0013A20040D75812. PANID:7,
Window is not full. Receive rate:4/7.
18/11/26 10:51:52.093|pool-37-thread-1|ClusterHead
Service [Info]
SensingData from 0013A20040D75812. PANID:7,
Window is not full. Receive rate:5/7.
18/11/26 10:51:52.102|pool-37-thread-1|ClusterHead
Service [Info]
SensingData from 0013A20040D75812. PANID:7,
Window is not full. Receive rate:6/7.
18/11/26 10:51:52.122|pool-37-thread-1|ClusterHead
Service [Info]
SensingData from 0013A20040D75812. PANID:7,
Window is full. Receive rate:7/7.
```

Fig. 21 After channel release.

work as an interference. As a result, some packets were dropped and the receive rate in the log was decreased as shown in Fig. 19. Specifically, some receive rates (see 3rd, 12th, and 24th lines) were 3/7 that do not satisfy the requested packet receiving rate p/q.

To overcome this situation, the CH requested *channel release* via sink node as shown in Fig. 20.

After the request, Wi-Fi AP paused to use the specified channel and ZigBee packets were successfly received again as shown in Fig. 21.

From the sequence of this experimentation, we confirmed that the prototype system works well.

5. Conclusions

In this paper, we designed specific procedures of the cooperative channel control method to improve the sink arrival rate of ZigBee packets allowing smaller degradation of Wi-Fi throughput in coexisting ZigBee and Wi-Fi networks proposed in [20]. In addition, we evaluated the performance of the proposed method using the *satisfaction rate* of ZigBee devices and Wi-Fi throughput as performance measures. Moreover, we confirmed the feasibility of the proposed methods by prototyping. Note that, in a very dense situation, the proposed method does not work well since the control packet cannot reach the sink. In practice, however, we assumed the owner of Wi-Fi APs and that of ZigBee devices are cooperative. In a typical case, they are the same. In such a case, all devices are expected to be distributed in a reasonable density.

In future work, environments where interference among several Wi-Fi networks occurs due to multiple APs and non-cooperative APs must be considered.

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References

[1] J. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami, “Internet of Things (IoT): A vision, architectural elements, and future directions,” Future Generation Computer Systems, vol.29, no.7, pp.1645–1660, 2013.

[2] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, “Internet of Things: A survey on enabling technologies, protocols, and applications,” IEEE Commun. Surveys Tuts., vol.17, no.4, pp.2347–2376, 2015.

[3] J. Lin, W. Yu, N. Zhang, X. Yang, H. Zhang, and W. Zhao, “A survey on Internet of Things: Architecture, enabling technologies, security and privacy, and applications,” IEEE Internet Things J., vol.4, no.5, pp.1125–1142, Oct. 2017.

[4] O. Novo, “Blockchain meets IoT: An architecture for scalable access management in IoT,” IEEE Internet Things J., vol.5, no.2, pp.1184–1195, April 2018.

[5] E. Benkhelifa, T. Welsh, and W. Hamouda, “A critical review of practices and challenges in intrusion detection systems for IoT: Toward universal and resilient systems,” IEEE Commun. Surveys Tuts., vol.20, no.4, pp.3496–3509, Fourthquarter 2018.

[6] IEEE Standard, “IEEE standard for information technology-telecommunications and information exchange between systems-local and metropolitan area networks-specific requirements-Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications,” IEEE Std 802.15.4-2006, pp.1–26, 2006.

[7] “IEEE standard for information technology–telecommunications and information exchange between systems–local and metropolitan area networks–specific requirements–part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications,” ANSI/IEEE Std 802.11, 1999 Edition (R2003), 2003.

[8] D. Yang, Y. Xu, and M. Gidlund, “Wireless coexistence between IEEE 802.11- and IEEE 802.15.4-based networks: A survey,” International Journal of Distributed Sensor Networks, vol.7, no.1, 2011.

[9] S. Pollin, I. Tan, B. Hodge, C. Chun, and A. Bahai, “Harmful coexistence between 802.15.4 and 802.11: A measurement-based study,” 3rd International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom 2008), pp.1–6, May 2008.

[10] J. Huang, G. Xing, G. Zhou, and R. Zhou, “Beyond co-existence: Exploiting WiFi white space for Zigbee performance assurance,” International Conference on Network Protocols (ICNP 2010), pp.305–314, 2010.

[11] C.j.M. Liang, N.B. Priyantha, J. Liu, and A. Terzis, “Surviving Wi-Fi interference in low power ZigBee networks,” Proc. 8th ACM Conference on Embedded Networked Sensor Systems (SenSys 2010), vol.104, no.1, pp.309–322, 2010.

[12] X. Wang and K. Yang, “A real-life experimental investigation of cross interference between WiFi and Zigbee in indoor environment,” 2017 IEEE International Conference on Internet of Things (iThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom) and IEEE Smart Data (SmartData), pp.598–603, June 2017.

[13] X. Zhang and K.G. Shin, “Cooperative carrier signaling: Harmonizing coexisting WPAN and WLAN devices,” IEEE/ACM Trans. Netw., vol.21, no.2, pp.426–439, 2013.

[14] S. Ishida, S. Tagashira, and A. Fukuda, “AP-assisted CTS-blocking for WiFi-zigbee coexistence,” 2015 Third International Symposium on Computing and Networking (CANDAR), pp.110–114, Dec. 2015.

[15] M.S. Kang, J.W. Chong, H. Hyun, S.M. Kim, B.H. Jung, and D.K.

Sung, "Adaptive interference-aware multi-channel clustering algorithm in a ZigBee network in the presence of WLAN interference," 2nd International Symposium on Wireless Pervasive Computing, Feb. 2007.
[16] S. Pollin, M. Ergen, M. Timmers, A. Dejonghe, L.D. Van Perre, F. Catthoor, I. Moerman, and A. Bahai, "Distributed cognitive coexistence of 802.15.4 with 802.11," 1st International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM 2006), pp.13–17, 2006.
[17] R. Musaloiu-E and A. Terzis, "Minimising the effect of WiFi interference in 802.15.4 wireless sensor networks," International Journal of Sensor Networks, vol.3, no.1, pp.43–54, Dec. 2008.
[18] L. Tytgat, O. Yaron, S. Pollin, I. Moerman, and P. Demeester, "Analysis and experimental verification of frequency-based interference avoidance mechanisms in IEEE 802.15.4," IEEE/ACM Trans. Netw., vol.23, no.2, pp.369–381, 2015.
[19] J.W. Chong, C.H. Cho, H.Y. Hwang, and D.K. Sung, "An adaptive WLAN interference mitigation scheme for ZigBee sensor networks," International Journal of Distributed Sensor Networks, vol.11, no.8, 2015.
[20] S. Nishikori, K. Kinoshita, Y. Tanigawa, H. Tode, and T. Watanabe, "A cooperative channel control method of ZigBee and WiFi for IoT services," 14th IEEE Annual Consumer Communications Networking Conference (CCNC 2017), pp.1–6, Jan. 2017.
[21] O. Younis and S. Fahmy, "HEED: A hybrid energy-efficient, distributed clustering approach for ad hoc sensor networks," IEEE Trans. Mobile Comput., vol.3, no.4, pp.366–379, Oct. 2004.
[22] T. Aramaki, K. Kinoshita, Y. Tanigawa, H. Tode, and T. Watanabe, "A congestion control method for multiple services on shared M2M network," 1st International Conference on Enterprise Architecture and Information Systems (EAIS 2016) in 5th International Congress on Advanced Applied Informatics (IIAI AAI 2016), July 2016.
[23] Qualnet Simulator version 7.1, Scalable Network Technologies, http://www.scalablenetworks.com

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