CDD: Coordinating Data Dissemination in Heterogeneous IoT Networks

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Traditional dissemination schemes were investigated for an isolated IoT network and did not fit the coexistence scenario of heterogeneous IoT networks. Motivated by the latest innovations in cross-technology communication (CTC) techniques, the authors propose CDD, a framework utilizing a WiFi-based access point (AP) to simultaneously conduct fast data diffusion in heterogeneous IoT networks (e.g., WiFi and ZigBee).

Abstract

Data dissemination in Internet of Things (IoT) networks provides a fundamental service for many critical applications. However, traditional dissemination schemes were investigated for an isolated IoT network, and did not fit the coexistence scenario of heterogeneous IoT networks. Motivated by the latest innovations in cross-technology communication (CTC) techniques, this article proposes CDD, a framework utilizing a WiFi-based access point (AP) to simultaneously conduct fast data diffusion in heterogeneous IoT networks (e.g., WiFi and ZigBee). We shed light on the network features in the coexistence scenario and then review the key challenges of coordinating dissemination based on CTC techniques. With these network features and challenges in mind, the CDD framework includes a series of designs to conduct efficient data dissemination in heterogeneous networks using a WiFi AP. The framework is implemented and evaluated on a real-world testbed. The results demonstrate that CDD can reduce the dissemination delay and significantly outperform the state-of-the-art approaches.

Introduction

As an important function, data dissemination is the process of diffusing data from a source node to all other nodes of a network. It can support time synchronization, node localization, code update, routing path formation, and so on. A robust dissemination scheme plays an important role in the performance of an Internet of Things (IoT) network. To date, a series of data dissemination schemes have been proposed. Guo *et al.* [1] and Zhu *et al.* [2] studied how to disseminate packets in low-duty-cycle wireless sensor networks (WSNs). Zhang *et al.* [3] improved the dissemination efficiency in the WiFi network by decoding one identical packet that was disseminated by different APs. Although these existing works have are effective in conducting efficient data dissemination, their research background was constrained in an isolated IoT network.

Under the ongoing paradigm of IoT, heterogeneous IoT networks communicating on the same unlicensed spectrum, that is, the industrial, scientific, and medical (ISM) band, inevitably coexist. For example, WiFi access points (APs) have been widely deployed as an infrastructure to access the Internet in houses, office buildings, marketplaces, and so on. Meanwhile, intelligent monitoring systems, smart lights, sweeping robots, and smart refrigerators using ZigBee networks are also employed in these spaces. Working on the same ISM spectrum, data dissemination in one IoT network must back off if another network is disseminating, and vice versa, which results in serious dissemination performance degradation. To address this issue, researchers (e.g., [4]) proposed software-defined networking for spectrum management, which dynamically adjusted transmissions of different senders based on channel status. However, such software-defined schemes do not work well in coexistence IoT radios with heterogeneous transmission powers (e.g., high-power WiFi and low-power ZigBee). This is because the high-power radio cannot sense the signal of its low-power counterpart, which is similar to the well-known hidden terminal problem in traditional IoT networks.

The recent breakthrough in cross-technology communication (CTC) techniques (e.g., WEBee [5] and LEGO-Fi [6]) provides the ability to transmit data between heterogeneous IoT radios. New challenges therefore emerge when applying these CTC techniques for efficient data dissemination in coexistence IoT networks. Specifically, the Cross-Technology channels built by CTC techniques generally suffers high packet loss [5] because of the inherent diversities of the heterogeneous radios. Moreover, the asymmetric communication ranges of heterogeneous IoT radios make it inefficient to exchange the acknowledgements (ACKs) during the dissemination process. It is therefore critical to conduct reliable and low-latency data dissemination via unreliable and asymmetric Cross-Technology channels.

To fill this gap, this article proposes cooperative data dissemination (CDD), a coordinated dissemination framework based on the recently developed CTC techniques (e.g., WEBee [5] and LEGO-Fi [6]). Specifically, we begin with a literature review of CTC techniques, which are the foundation of CDD. Then we dive into the coexistence networks' features and review the challenges in using CTC techniques for data dissemination in such a coexistence scenario. In CDD, one WiFi AP leverages the parallel CTC technique [7] to disseminate heterogeneous packets simultaneously. To address the unreliable WiFi-to-ZigBee channel, the AP retransmits ZigBee packets to improve the reliability. The retransmission design considers the unreliable CTC channel, and the durations of both

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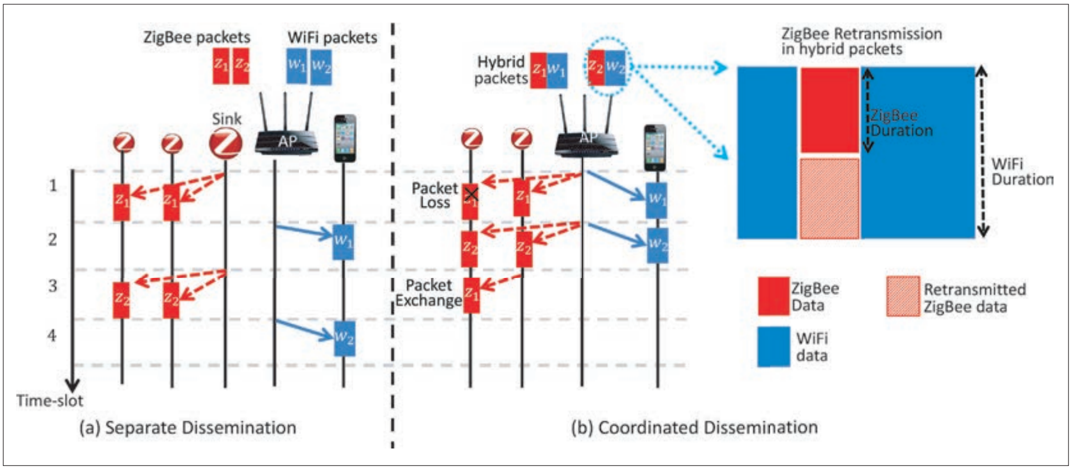

Figure 1. Comparison of traditional data dissemination scheme and CDD: a) traditional separate dissemination; b) CDD based on the parallel CTC technique [7].

The encouraging advances in CTC techniques open a new direction to the research of coordinating coexistence IoT networks. Different from these existing works focus on the physical layer, this article leverages the CTC techniques for further performance improvement at the network layer.

WiFi and ZigBee packets. Moreover, a local packet exchange strategy in the low-power ZigBee network is designed to reduce redundant retransmissions. To address the asymmetric communication ranges of WiFi and ZigBee, the transmission schedule information in heterogeneous networks is exchanged using the ZigBee-to-WiFi technique. In this way, the high-power AP could dynamically occupy the wireless channel to reduce the interference to the low-power ZigBee network, while guaranteeing the dissemination performance. The advantage of the CDD framework is verified by a real-world testbed consisting of 20 ZigBee nodes, followed by the implications for future research directions in coordinative frameworks for heterogeneous IoT networks.

Related Work

In recent years, there has been a rich literature on CTC techniques, which builds the direct communication channel between heterogeneous IoT radios. Therefore, only the works that are most relevant to the CDD framework are reviewed.

Early works on CTC techniques are achieved by manipulating the packet-level features. Howies [8] encodes ZigBee bits by adjusting the WiFi packet length. Freebee [9] and EMF [10] embed the cross-technology information by shifting the transmission time of packets. B2W2 [11] transmits the information using the channel state information (CSI). DopplerFi [12] encodes information by injecting artificial Doppler shifts in the signal; heterogeneous receivers can decode the information from patterns in the Gaussian frequency shift keying (GFSK) demodulator and CSI. Since these packet-level features are easy to access by different radios, these packet-level CTC techniques are usually bidirectional. Because of the coarse-grained packet-level modulation, the throughputs of these packet-level techniques are limited by 0.5–7 kb/s.

The latest representative CTC technique, WEBee [5], builds a WiFi-to-ZigBee channel with a high throughput of 126 kb/s. The rationality of WEBee is that some WiFi quadrature amplitude modulation (QAM) constellation points are close to the ZigBee offset quadrature phase shift keying (OQPSK) constellation points. One WiFi sender can emulate the time domain waveform of ZigBee by selecting specific QAM points. ZigBee receivers can decode the WiFi signal using the OQPSK demodulation. Working on the same ISM band, the narrow ZigBee channel (e.g., 2 MHz) overlaps with a part of the wide WiFi channel (e.g., 20 MHz). Observing this, the parallel CTC technique PMC [7] utilizes a part of the WiFi subcarriers to disseminate ZigBee data as WEBee does, and the remaining ones to disseminate WiFi data. The ZigBee receiver can receive the ZigBee data on the ZigBee channel. The WiFi receiver can receive the WiFi data by omitting the payload corresponding to the ZigBee channel. By using the remaining WiFi subcarriers, PMC achieves much higher spectrum efficiency.

Guo *et al.* [6] proposed LEGO-Fi, the latest high-throughput communication technique from ZigBee to WiFi by leveraging cross-demapping. In LEGO-Fi, one WiFi receiver distinguishes a ZigBee packet via the periodicity of the ZigBee packet's preamble. Then the rich processing capacity of a WiFi receiver can decode the ZigBee data with the solution for the pattern identification problem. The throughput of LEGO-Fi reaches 213 kb/s. LEGO-Fi builds the channel for ZigBee nodes to notify the WiFi AP of network status (e.g., duty cycle) so that the WiFi AP may schedule the channel occupation to balance the dissemination requirements in both IoT networks.

The encouraging advances in CTC techniques open a new direction in the research of coordinating coexistence of IoT networks. Different from these existing works, focused on the physical layer, this article leverages the CTC techniques for further performance improvement at the network layer.

Challenges and CDD Overview

Figure 1 compares traditional separate data dissemination schemes and CDD. In the traditional separate data scheme in Fig. 1a, one ZigBee packet and one WiFi packet are disseminated in two different time slots, because the ZigBee transmission has to back off due to the ongoing WiFi transmission, and vice versa. In CDD, depicted in Fig. 1b, one WiFi AP concurrently disseminates one ZigBee packet and one WiFi packet during time slots 1 and 2. The advantage of CDD is obvious, because only one time slot is required

The three-stage CDD aims to address the two challenges. The first stage, Retransmission, improves the reliability of the CTC channel. The second stage, Local Packet Exchange, reduces the redundant retransmissions. The last stage, Dynamic Channel Occupation, dynamically occupy the channel to balance the transmission in both WiFi and ZigBee networks.

to disseminate the two heterogeneous packets. In the case of packet loss, lost packets can be exchanged locally in the ZigBee network when the channel is available such as during time slot 3.

However, the first critical challenge of CDD is that the CTC channels are unreliable. The reason is that the Euclidean distances between the WiFi QAM points and the ZigBee OQPSK points are non-zero, which inevitably results in a certain degree of distortion when emulating [5]. For example, the packet reception ratios (PRRs) of the WiFi-to-ZigBee techniques [5, 7] are only around 50 percent. Moreover, the latest ZigBee-to-WiFi technique, LEGO-Fi, is only about 85 percent. The second challenge is that the communication range of one WiFi AP is generally much longer than that of ZigBee nodes, because the AP is generally wire-powered while ZigBee nodes are battery-powered. The asymmetric communication ranges bring heavy communication overhead for ZigBee nodes to send ACKs back to the AP, and seriously limit the performance improvement of the coordinative dissemination.

With the analysis above, CDD includes three stages:

- *Retransmission by AP:* Because of the unreliable WiFi-to-ZigBee channel, the AP needs to retransmit ZigBee packets to improve the dissemination reliability. To reduce redundant retransmissions, the AP just transmits one ZigBee packet a limited number of times. In CDD, the AP does not require any specific ZigBee node to receive the packet, but transmits a limited number of duplicate ZigBee packets to the ZigBee network. The right part of Fig. 1b demonstrates one hybrid WiFi packet with two duplicate ZigBee packets via the parallel CTC technique [7].
- *Local Packet Exchange:* When one ZigBee node fails to receive one packet because of the unreliable CTC channel, its neighbors may have received the packet. The packet can be exchanged among the nodes instead of being retransmitted by the AP. CDD includes a network-coding-technique-based packet exchange scheme. After one node receives one packet, it sends the ACK back to the AP. In the ZigBee network, the ACKs of multiple packets from multiple nodes can be aggregated to reduce the traffic in the ZigBee network.
- *Dynamic Channel Occupation:* The data dissemination by the high-power AP will occupy the channel and interfere with the ACK aggregation and packet exchange in the ZigBee network. As shown in Fig. 1b, the lost ZigBee packet can only be exchanged during time slot 3 because the AP takes up the channel during time slot 2. The AP should dynamically occupy the channel to balance the dissemination requirements in both IoT networks.

The three-stage CDD aims to address the two challenges. The first stage, *retransmission*, improves the reliability of the CTC channel. The second stage, *local packet exchange*, reduces the redundant retransmissions. The last stage, *dynamic channel occupation*, dynamically occupies the channel to balance the transmission in both WiFi and ZigBee networks.

CDD Design

Built upon the CDD framework overview above, the three-stage designs are introduced in detail.

Retransmission by AP

Consider that there are multiple WiFi packets and multiple ZigBee packets in the WiFi AP. Generally, the WiFi packet duration and ZigBee packet duration are different. For example, the duration of one WiFi packet is [1 μs, 10 ms], while that of a ZigBee packet satisfies [200 μs, 4 ms] [7]. To disseminate the heterogeneous packets using the parallel CTC technique, the packets' durations should be adjusted first.

If one WiFi packet's duration is longer than 4 ms, it should be divided into multiple shorter ones with a duration no longer than 4 ms; if one WiFi packet's duration is shorter than 4 ms, multiple short WiFi packets are aggregated into one aggregated packet using the aggregate MAC service data unit (A-MSDU) function of WiFi standards [7]. The duration of the aggregated packet should be as long as possible within 4 ms.

Given a deployed ZigBee network, the AP needs to receive the duty cycle information and the PRRs from the AP to ZigBee nodes as described later. Then ZigBee packets' durations also need to be adjusted based on the new WiFi packet duration. Specifically, the PRR of the WiFi-to-ZigBee channel decreases as the ZigBee packet duration increases [5]. To increase reliability, one WiFi packet can include multiple duplicates of one ZigBee datum. The right part of Fig. 1b illustrates an example when two ZigBee data duplicates are transmitted along with a WiFi packet. The AP can estimate the average total number of ZigBee packets received by a ZigBee node and the node's neighbors, which should be larger than a *required number* ≥ 1. The trade-off between the total number of transmissions and the dissemination reliability can be achieved by an appropriate *required number*. Clearly, a larger *required number* requires the AP to retransmit one packet more, which increases the reliability; while a smaller *required number* reduces redundant retransmissions at the expense of dissemination reliability. For ease of representation, the condition in which the average total number of a ZigBee packet received by a node and the node's neighbors being larger than *required number* is called a *reliable condition*.

Based on the WiFi packet duration above, an efficient fixed point iteration (FPI) method can be employed to determine ZigBee packets' shortest duration and number of duplicate ZigBee packets in a WiFi packet so that one ZigBee packet's total expected received number is larger than the *required number*. Specifically, starting with the maximum ZigBee duration of 4 ms, FPI determines the maximum number of retransmissions along with the WiFi packet. Then FPI estimates if the *reliable condition* holds. If the *reliable condition* holds, the ZigBee packet duration is reduced by a small interval (e.g., the ZigBee symbol duration 4 μs). FPI repeats this process until it returns the shortest ZigBee packet duration satisfying the *reliable condition*.

One naive dissemination option of the AP is to naively disseminate the *required number* of all

ZigBee packets for each ZigBee node, which is, however. not effective for low-duty-cycle ZigBee networks. On the other hand, the AP can disseminate a limited number of ZigBee packets to the whole ZigBee network, and then the nodes can exchange the received packets in case of packet loss. Disseminating this limited number of ZigBee packets is closely related to the channel occupation, which is presented along with *dynamic channel occupation* later.

Distributed ZigBee Data Exchange

Based on the design above, there are four kinds of packets that would be exchanged in the ZigBee network:

- Duty cycle information of nodes: When one node changes its duty cycle and replenishes its PRR, it updates the latest information to the AP by multihop and LEGO-Fi. The AP sends an ACK to the node after receiving the information; otherwise, the node repeats to update the information.
- Requests for lost packets: Each packet sent by the AP has an ID, and the receiving node can be aware of the IDs of lost packets. In this case, the node should request the lost packets from its neighbors.
- Lost packets: If a node receives a request for lost packets from its neighbor, it leverages the network-coding-based packet exchange method below to transmit packets to its neighbors.
- ACKs for received packets: When one node receives a packet from the AP or its neighbor, it sends one ACK back. If receiving multiple packets, the node can aggregate the ACKs and send only one ACK packet to reduce the communication overhead.

Network-Coding-Based Packet Exchange: When the channel is available, the nodes compete for the wireless channel to request the lost packets from their neighbors. During the exchange process, one node employs a network-coding-based method to transmit the packets to neighbors. Consider the two nodes in Fig. 2 requesting for lost packets: *node 1* and *node 2* request of a common neighbor *node 3* lost packets *packet1* and *packet2*, respectively. During time slot 2 or 4, *node 3* competes for the channel and disseminates *packet1* and *packet2* to *node 1* and *node 2*, respectively. During time slot 3, *node 3* disseminates the coded packets *packet1* ⊕ *packet2*, where ⊕ is the *xor* operation. For *node 1*, if it has received *packet2* earlier, it can decode *packet1* as *packet1* ⊕ *packet2* ⊕ *packet2*. Similarly, *node 2* can decode *packet2* as *packet1* ⊕ packet2 ⊕ *packet1*. This network-coding-based packet exchange only requires *xor* operation of the packet, which can be processed easily by current low-power ZigBee nodes. If one node cannot receive all packets after requesting to all its neighbors, the AP cannot receive the ACK. In this case, the AP continues disseminating the packets.

Dynamic Channel Occupation by AP

The exchange of these packets among the ZigBee network may interfere with transmission by the AP. To reduce the interference, the AP should dynamically take up or release the channel based on the duty cycle information of the ZigBee network and the transmission requirements in both networks. An efficient channel occupation algorithm for the AP is presented as follows:

- If there is one ZigBee packet to disseminate along with WiFi packets, the AP takes up the time slots during which the maximum number of ZigBee nodes are in listening state (e.g., time slot 3 in Fig. 2) until all nodes or their neighbors have received the *required number* of ZigBee packets.
- If the AP receives a request for a lost packet from a ZigBee node, the AP needs to disseminate the lost packet and minimize the total time slots for dissemination, while guaranteeing that one node and its neighbor nodes receive the *required number* of packets.
- If no more ZigBee packets need to be disseminated, the AP will take up the time slots during which the minimum number of nodes are in listening state (e.g., time slot 1 in Fig. 2) so that the interference to the packet transmission in the ZigBee network is minimized.

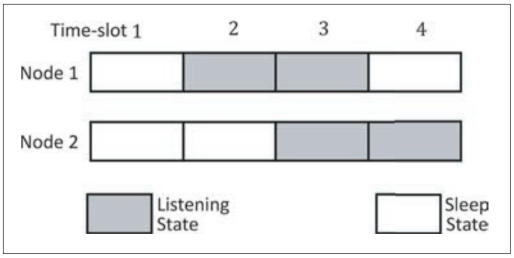

Figure 2. Duty cycle example of two ZigBee nodes.

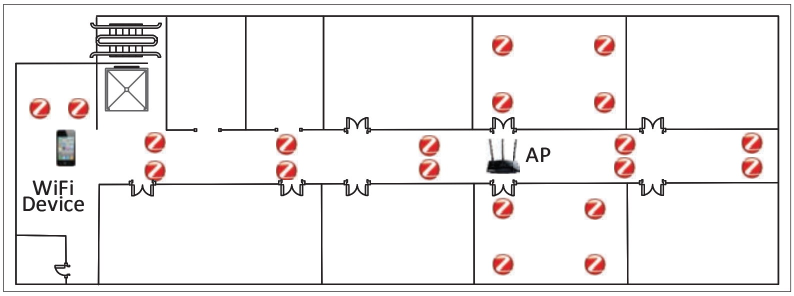

Figure 3. Testbed deployment in hallway and labs.

Evaluation

To thoroughly evaluate the performance of CDD, one CDD WiFi AP and one WiFi receiver with the IEEE 802.11 b/g stack are implemented on two USRP N210 platforms. The ZigBee network consists of 20 off-the-shelf TelosB nodes equipped with Tinyos, which are 802.15.4-compliant. The AP and WiFi receiver are placed on a desk and a rolling chair, and ZigBee nodes are placed on the ceiling of the hallway and lab rooms, as demonstrated in Fig. 3. The latest dissemination approaches, PANDO [13] and a naive coordinating data dissemination (NCDD) scheme, are also implemented as benchmarks. NCDD applies no retransmissions or dynamic channel occupation. The evaluation results are demonstrated in Figs. 4 and 5.

Impact of WiFi Occupation Ratio

Figure 4 illustrates the average dissemination delay with respect to the WiFi occupancy ratio of the channel. When the WiFi occupancy ratio is

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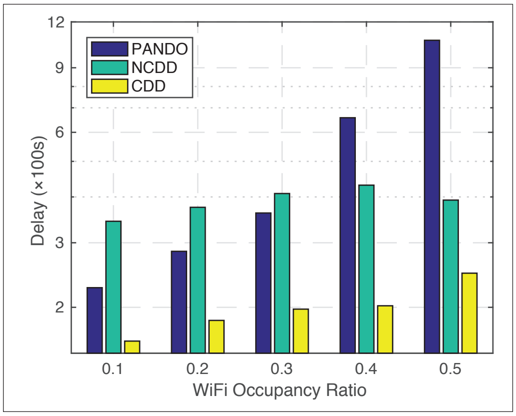

Figure 4. Dissemination delay vs. WiFi occupancy ratio.

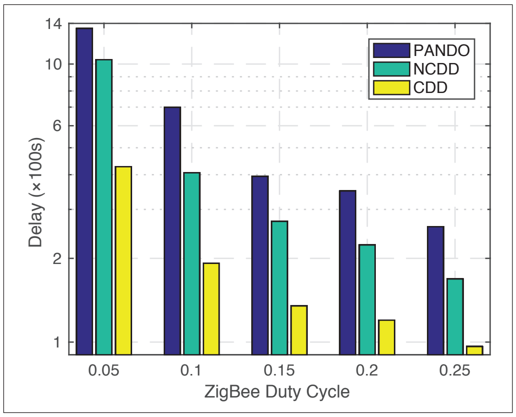

Figure 5. Dissemination delay vs. ZigBee duty cycle.

low (≤ 0.3), the dissemination delay of PANDO is similar to those of CDD and NCDD, because the dissemination traffic in the WiFi network is low, and the interference between the two networks is ignorable. As the WiFi occupancy ratio increases, the delay of PANDO increases seriously, while those of CDD and NCDD remain stable. When the occupancy ratio reaches 0.5, the delay of CDD is 238.3 s, which is only 22.3 percent of the delay by PANDO (1068 s). If the channel is more crowded, CDD can achieve larger superiority than the non-cooperative dissemination scheme PANDO. This is because the ZigBee data in CDD and NCDD is disseminated by the high-power AP by only one hop, while that in PANDO is disseminated by multihop in the ZigBee network. Moreover, the dissemination of PANDO in each hop may be interfered by the WiFi data, which results in long delay in PANDO; while the ZigBee data is transmitted together with the WiFi packet simultaneously, and the interference is reduced. Thus, the delay of CDD and NCDD is significantly reduced.

Impact of Duty Cycle

Figure 5 illustrates the dissemination delay with respect to the duty cycle of the ZigBee network. As the duty cycle increases, the delay achieved by PANDO and NCDD reduces rapidly, while that of CDD remains relatively stable. This is because CDD benefits from local data exchange and the dynamic channel occupation by the AP. When the duty cycle is low, CDD achieves a short delay by exchanging the data locally. The average dissemination delay of CDD is reduced by 2.96× compared with PANDO. In NCDD, its average delay is 1.61× to 2.42× longer than that of CDD, due to the inefficiency of the WiFi-to-ZigBee channel. Thus, it is concluded that the proposed CDD scheme can effectively reduce the dissemination delay and improve the network performance in the crowded channel.

Future Research Directions

In the aforementioned coexistence scenario, many aspects deserve further research, which are classified into three categories: *improving the reliability of the CTC channel*, *coordinating other data transmission*, and *coordinating other heterogeneous IoT networks*.

Improving the Reliability of CTC Channels: In the power-domain non-orthogonal multiple access (NOMA) [14], one WiFi sender changes the positions of the QAM constellation points by superimposing multiple signals. Motivated by this, we can superpose the WiFi signal and a specific noise so that the Euclidean distance of the selected QAM points to the OQPSK points is reduced, and the reliability of the CTC channel therefore may be improved. There is a need to carefully determine the appropriate noise to superpose the WiFi signal in order to emulate a better ZigBee waveform.

Coordinating Other Data Transmission: This article studies data dissemination using CTC; other data transmission methods such as data aggregation and machine-to-machine communication remain open and hot topics for research. For example, for the energy-balanced data aggregation in the ZigBee network, the WiFi AP should take up the leaf nodes' active time with higher probability and reserve the channel during the active time of the nodes near the sink. The leaf nodes need to retransmit more, while the nodes near the sink need to retransmit less. The retransmissions consume extra energy, which can therefore mitigate the ZigBee energy hole problem. However, there is a need for the design of coordination strategies and distributed data transmission protocols for different objectives (e.g., energy balance, transmission reliability, energy efficiency, and data delay).

Coordinating Other IoT Networks: Some advances have been made on some CTC channels recently; however, it is nontrivial to build high-throughput a cross-technology channel between other CTC channels because of the incompatibility of the heterogeneous IoT radios. For example, the throughput of the latest Bluetooth-to-WiFi techniques [12] are only 7 kb/s, which is much lower than those of the WiFi and Bluetooth standards. Similar heterogeneous coexistence scenarios also exist on other unlicensed bands. For example, LTE operators have begun to use the 5 GHz ISM band, which currently is mainly used by WiFi. CTC is also a promising technique to coordinate the two coexistence heterogeneous networks [15]. However, the throughput of the latest LTE-to-WiFi technique [15] is only 665 b/s, which cannot be used to exchange a large volume of data (e.g., software updating data) between the heterogeneous IoT networks. With this constraint, one research direction is to improve the throughput of these cross-technology channels at the physical layer, as stated above. Another direction is to leverage the limited cross-technology channels for exchanging important information (e.g., the duty cycle, neighbor status, and link quality) to coordinate these networks. Therefore, there is a need to design coordinating strategies using such low throughput.

Conclusion

The CDD framework introduced in this article is to improve the dissemination performance in a coexistence scenario with heterogeneous IoT networks. The proposed framework is very effective, not only because heterogeneous packets are disseminated concurrently, but also due to the series of designs to improve the dissemination reliability on the lossy WiFi-to-ZigBee channel. More specifically, the WiFi AP first retransmits ZigBee packets along with WiFi packets simultaneously using the latest parallel CTC technique. The retransmission considers the unreliable CTC channels as well as the durations of both WiFi and ZigBee packets. The ZigBee packets are disseminated to the whole ZigBee network instead of any specific target node. Then the ZigBee nodes can exchange the lost packets using a network-coding-based scheme. Moreover, the AP dynamically releases the channel for the packet exchange in the ZigBee network or takes up the channel time for dissemination in the WiFi network to coordinate the dissemination processes in both networks. Evaluations based on a real-world testbed show that CDD can significantly reduce the dissemination delay. Finally, some future research directions deserving more efforts for heterogeneous IoT networks are pointed out.

Acknowledgments

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