Exploiting WiFi AP for Simultaneous Data Dissemination among WiFi and ZigBee Devices

Wei Wang, Xin Liu, Yao Yao and Ting Zhu
Department of Computer Science and Electrical Engineering
University of Maryland, Baltimore County
Email: {ax29092, xinliu1, of90379, zt}@umbc.edu

***Abstract*—Recent advances in Cross-Technology Communication (CTC) have opened a new door for cooperation among heterogeneous IoT devices to support ubiquitous applications, such as smart homes and smart offices. However, existing work mainly focuses on physical layer performance improvements. In this paper, we explore how to leverage the latest CTC techniques for network layer performance improvements. Specifically, we introduce Waves, which leverages WiFi to ZigBee CTC and WiFi access point's adaptive transmit power control techniques for reliable and fast data dissemination in low-duty-cycle ZigBee networks. We extensively evaluate our design under various settings. Evaluation results show that Waves can provide reliable data dissemination and is 33.5 times faster than the state-of-the-art protocol in terms of dissemination time.**

I. Introduction

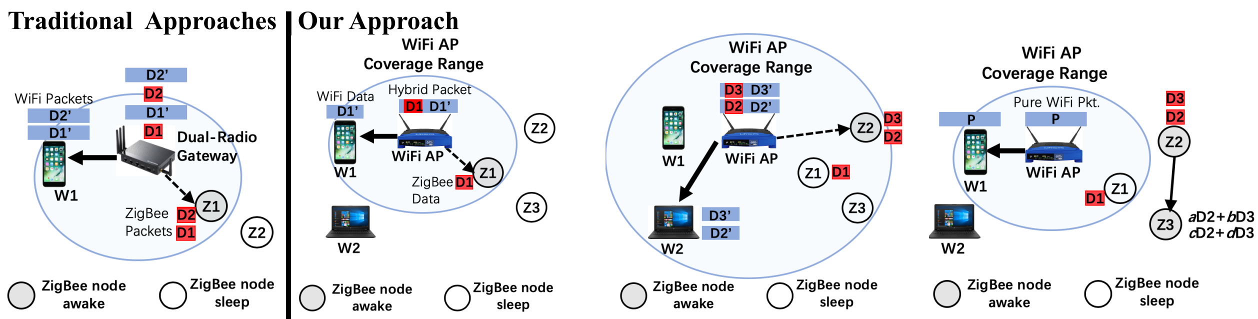
The exponentially increasing number of IoT devices leads to densely coexisting wireless technologies in the unlicensed spectrum (i.e., ISM bands). To leverage the unique features of coexisting wireless technologies, researchers have proposed cross-technology communication (CTC) techniques [42], [24], [26], [11] that enable direct communication between WiFi and ZigBee without requiring any additional hardwares (e.g., gateways). One of the most recent CTC techniques – WEBee [26] enables high throughput communications among commodity WiFi and ZigBee devices. By controlling the WiFi's payload, WEBee emulates the ZigBee signal that can be demodulated at the commodity ZigBee node. Since WEBee utilizes only 7 out of 64 WiFi subcarriers that are overlapped with the ZigBee channel to conduct signal emulation, the remaining majority of WiFi subcarriers are still able to transmit WiFi data. As demonstrated in PMC [11], the WiFi device can conduct parallel WiFi-to-WiFi and WiFi-to-ZigBee communications by using a single WiFi data stream.

The advances in CTC techniques at the physical layer are very encouraging. However, little work has been proposed to explore the network layer design for physical layer CTC techniques. To fill this gap, we introduce Waves, which leverages WiFi to ZigBee CTC and WiFi access point's adaptive transmit power control techniques for reliable and fast data dissemination in low-duty-cycle ZigBee networks. Figure 1 shows the difference between a traditional approach and our approach. As shown in Figure 1 (a), when the WiFi-ZigBee dual-radio gateway needs to send out the ZigBee packets and WiFi packets, the gateway has to send out packets in different time slots to avoid collisions with the WiFi and ZigBee devices. In our approach (see Figure 1 (b)), the WiFi AP broadcasts hybrid packets that contain both ZigBee data and WiFi data using the latest CTC techniques [26], [11]. The ZigBee data and WiFi data can be demodulated by corresponding commodity ZigBee and WiFi devices. To minimize the interference with other coexisting IoT devices and save energy, the WiFi AP uses the adaptive transmission power control technique, which has been defined in IEEE 802.11 standard [4] and proved to be very effective by many researchers [34], [35], [37]. Therefore, when the WiFi AP needs to send packets to another WiFi device (e.g., $W2$ in Figure 1 (b)), it increases its transmission power, which also enables the WiFi AP to reach ZigBee node $Z2$ (shown in Figure 1 (c)). In our design, we use fountain code to encode the ZigBee-WiFi hybrid packets to enable reliable communication from WiFi AP to ZigBee nodes under unreliable wireless communication environments. After the WiFi AP sends out sufficient ZigBee-WiFi hybrid packets to ZigBee nodes, it can send pure WiFi packets to WiFi devices. ZigBee nodes can propagate the data dissemination inside the low-duty-cycle ZigBee networks (in Figure 1 (d)). In addition, we use linear network coding to encode the ZigBee-to-ZigBee packets and further reduce the redundant transmissions.

The advantages of Waves are as follows: i) it seamlessly enables the simultaneous WiFi-to-WiFi communication and ZigBee data dissemination. Unlike traditional protocols that treat WiFi-to-WiFi communication as interference and force ZigBee nodes to back-off, our hybrid ZigBee-WiFi packet transmissions significantly reduce the ZigBee data dissemination delay; and ii) since WiFi devices normally transmit at 20dBm while ZigBee nodes transmit at 0dBm, the WiFi AP has a much larger communication range than that of ZigBee-to-ZigBee communication. Therefore, the WiFi AP can cover a greater number of ZigBee nodes in each transmission, which further reduces the delay.

To transform the idea behind Waves into a practical system, we need to overcome the following three main challenges. First, the WiFi device does not know the working schedule of the ZigBee node. Different from traditional homogeneous IoT networks (i.e., WiFi network or ZigBee network), it is difficult for the ZigBee to inform WiFi of its working schedule. This is because the ZigBee to WiFi communication is packet-level CTC. It requires the ZigBee device to generate duplicated

978-1-6654-4131-5/21/$31.00 ©2021 IEEE



(a) The dual-radio gateway sends out ZigBee packets and WiFi packets at different time slots to avoid collisions at the WiFi and ZigBee devices.

(b) WiFi AP broadcasts hybrid packets to W1 and Z1 using low transmit power to achieve simultaneous WiFi and ZigBee data delivery.

(c) WiFi AP broadcasts hybrid packets to W2 and Z2 using high transmit power. Z3 is asleep, so it cannot receive packets from WiFi AP.

(d) When WiFi AP is sending pure WiFi packets to W1, Z2 can forward the ZigBee data to Z3 using linear network coding after Z3 is awake.

Fig. 1. Compared to traditional approaches, our approach enables the simultaneous WiFi-to-WiFi communication and ZigBee data dissemination. Therefore, it can achieve more efficient spectrum utilization and significantly reduce the delay in ZigBee networks.

packets to transmit several bits [24], [42], [9], which may introduce a huge overhead to the network. *To overcome this challenge, we introduce a Cross-technology Sensing approach that only requires the WiFi device to passively sense the ZigBee network without introducing additional traffic.* Second, the traditional WiFi adaptive power control is designed for improving the spectral efficiency and reducing the interference in the WiFi network [19], which does not take CTC and the ZigBee traffic into consideration. Simply determining the transmission power based on the WiFi network may result in reducing the ZigBee network performance. *To overcome this challenge, we model the interference in the WiFi and ZigBee coexistence network and introduce a transmission power optimization method to determine the WiFi transmission power.* Third, the WiFi does not know the transmission status from the WiFi to ZigBee communication. In the traditional ZigBee network, the sender can expect the receiver to transmit acknowledgements (ACKs) to guarantee data dissemination reliability. However, due to the large overhead introduced by packet-level ZigBee to WiFi communication, this approach is not applicable. *To overcome this challenge, we propose a Distributed Fountain Codes Transmission scheme, which does not require feedbacks from the receiver. Moreover, this technique has the additional advantage of improving the data dissemination reliability.*

In summary, the contributions of this paper are as follows:

• To the best of our knowledge, this is the first work that investigates how to use CTC for providing reliable and fast data dissemination in ZigBee networks. We believe that the design principles and challenges in Waves are generic and applicable to a whole set of future heterogeneous IoT network layer design that leverages CTC for further performance improvements.

• We design a WiFi AP Initiated Dynamic Broadcasting (WIDB) to find the optimal solution for the WiFi device to control its transmission power. We also introduce a Distributed Fountain Codes Transmission (DFCT) techniques to conduct reliable data dissemination from WiFi to ZigBee.

• We implemented our design on USRP and TelsoB nodes and extensively evaluated our design under different settings. The evaluation results demonstrate that Waves is reliable and 33.5 times faster than the state-of-the-art protocol in terms of the dissemination time.

II. Key Mechanisms in Waves

Our goal is to provide fast and reliable data dissemination in WiFi and ZigBee coexistence networks. To do this, there are two key mechanisms in Waves:

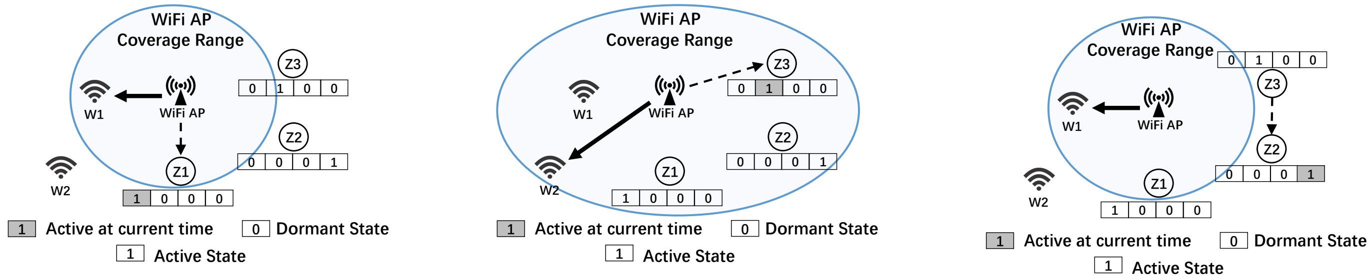
• **WiFi AP Initiated Dynamic Broadcasting (WIDB):** Waves utilizes the WiFi AP to conduct data dissemination for ZigBee nodes. By leveraging WiFi adaptive power control, the packets are transmitted to ZigBee nodes at different distances, which avoids cross-technology interference (CTI) and reduces the delay introduced by the low duty-cycle of ZigBee nodes.

• **Distributed Fountain Codes Transmission (DFCT):** To enable reliable data dissemination and reduce the impact on the WiFi-to-WiFi communication, we introduce a Distributed Fountain Codes Transmission technique which only requires the WiFi AP to deliver a limited number of coded packets to a subset of ZigBee nodes inside the ZigBee networks. As a result, Waves can conduct reliable data dissemination and has little impact on original WiFi-to-WiFi communications.

A. Benefits of WIDB

The mechanism of WiFi AP initiated dynamic broadcasting allows the WiFi AP to conduct data dissemination for ZigBee nodes. In contrast, traditional approaches may face high CTI from the WiFi traffic [29], [18], [39] and may not conduct data dissemination due to the Carrier Sense Multiple Access (CSMA) scheme adopted by ZigBee nodes. Even if we assume that ZigBee nodes do not encounter CTI, the multi-hop transmissions in low-duty-cycle ZigBee networks still introduce high delays.

In Waves, we leverage the WiFi adaptive power control to overcome this challenge. Specifically, the transmission power of a typical WiFi AP can dynamically change from 0dBm to



(a) WiFi AP simultaneously transmits WiFi packets and ZigBee packets to $W1$ and $Z1$, respectively.

(b) By controlling the transmission power, WiFi AP can communicate with $W2$ and $Z3$. The corresponding delay is only two time slots.

(c) WiFi AP is communicating with $W1$ while $Z3$ can transmit received packets to $Z2$.

Fig. 2. An example of WiFi AP Initiated Dynamic Broadcasting

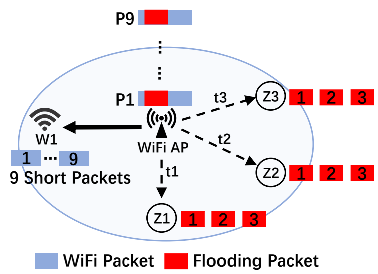


Fig. 3. The WiFi AP transmits coded packets to $Z1$, $Z2$ and $Z3$ during their wake up time $t1$, $t2$, and $t3$, respectively.

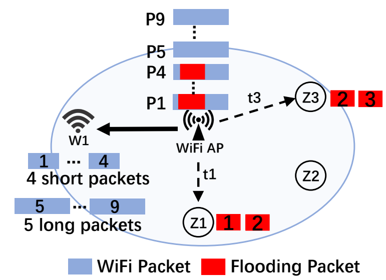


Fig. 4. The throughput of WiFi AP to $W1$ is much higher since only 4 out of 9 WiFi packets are short packets.

20dBm. As the WiFi AP changes its transmission power to communicate with other WiFi devices, it can simultaneously conduct data dissemination to the ZigBee nodes at different distances. By doing this, we can reduce the number of hops, reduce the CTI and significantly reduce the delay. For the sake of clarity, a simplified example is shown in Figure 2(a). In the first time slot, the WiFi AP is communicating with $W1$. Since $Z1$ is active, the WiFi AP simultaneously transmits ZigBee data to $Z1$ and WiFi data to $W1$ using ZigBee-WiFi hybrid packets. Then, as shown in Figure 2(b), the WiFi AP increases the transmission power to communicate with $W2$ at the second time slot. Since $Z3$ is active, the WiFi AP can simultaneously transmit packets to $Z3$. At the fourth time slot, the WiFi AP communicates with $W1$ again (in Figure 2(c)). Since $Z2$ and $Z3$ are not interfered by the WiFi AP, $Z3$ can transmit received packets to $Z2$. In this example, instead of waiting for multi-hop transmissions in the ZigBee device and avoiding the CTI, each ZigBee node receives the data after switching to the active state. **In summary**, *WiFi AP initiated dynamic broadcasting can avoid the CTI and significantly reduce the data dissemination delay.*

B. Benefits of DFCT

Normally, the sender expects the receiver to transmit acknowledgements (ACKs) to guarantee the data dissemination reliability. However, in CTC networks, although several approaches have enabled ZigBee-to-WiFi CTC [24], [10], [11], it is still difficult for ZigBee nodes to transmit ACKs to the WiFi AP due to the following reasons: i) Since the WiFi AP is transmitting packets to other WiFi devices, it cannot receive ZigBee packets at the same time; ii) Current WiFi-to-ZigBee and ZigBee-to-WiFi CTC are based on different techniques. For instance, the communication from ZigBee to WiFi may be based on packet-level CTC, which requires the ZigBee nodes to generate a huge number of packets to initiate the ZigBee to WiFi communication. These generated packets will introduce high network overhead and interfere with the ongoing WiFi-to-WiFi communications.

In Waves, the WiFi AP uses fountain codes to encode ZigBee packets for reliable data dissemination. Prior work [15] requires the sender to keep transmitting the coded packets until receiving the ACKs from them. However, since the WiFi needs to sacrifice its overlapped subcarriers to communicate with ZigBee device, simply applying prior approach will reduce the WiFi throughput. As shown in Figure 3, assume each ZigBee node requires 3 coded packets to decode the ZigBee data. Therefore, the WiFi AP should deliver 3 coded packets during each ZigBee node's active state. The total number of hybrid packets transmitted from the WiFi AP is 9 while the WiFi device $W1$ only receives 9 short packets, which reduces the throughput from the WiFi AP to $W1$.

To address this issue, Waves introduces a distributed fountain codes transmission technique, which only requires the WiFi AP to dynamically transmit coded ZigBee packets to a limited number of ZigBee nodes and does not require a specific ZigBee node to receive coded packets. When transmitting enough packets to the ZigBee network, the WiFi AP can terminate the data dissemination. We give an example in Figure 4. Assume the ZigBee nodes need to receive 3 coded packets to perform decoding. However, due to the current WiFi traffic status, the WiFi AP can only transmit 2 coded packets to $Z1$ and $Z3$ during their active states, respectively. In this example, $Z1$ receives packet 1 and 2 while $Z3$ receives packet 2 and 3. Since there are already **four** coded packets in the network, the WiFi AP can stop transmitting the hybrid packets and transmit pure WiFi packets to $W1$. The ZigBee nodes can exchange the received packets in the ZigBee network when they do not interfere with the WiFi traffic. In this example, the WiFi AP only transmits 4 hybrid packets and the remaining 5 packets are pure WiFi packets. **In summary**, *Waves can conduct reliable data dissemination and reduce the influence on the ongoing WiFi traffic*.

III. Detailed Protocol of Waves

The design of Waves mainly consists of three steps.

1. **Cross-technology Sensing and Transmission Power Optimization:** The WiFi devices sense the channel to learn the working schedules of ZigBee nodes. Then, according to the WiFi traffic, the WiFi AP controls its transmission power to conduct transmissions to WiFi devices and ZigBee nodes simultaneously.
2. **ZigBee Data Dissemination:** To improve the data dissemination reliability and reduce the network overhead, the data disseminated to the ZigBee device is encoded by using the Distributed Fountain Codes Transmission technique. The WiFi AP will terminate the dissemination immediately when transmitting enough coded packets to the ZigBee network.
3. **Packets Exchange in ZigBee Network**: To cover the whole network and improve the data dissemination reliability, a ZigBee node can exchange the received packets to its neighboring nodes. To reduce the number of redundant transmissions, each ZigBee node leverages the network coding technique to improve the packet exchange efficiency.

A. Cross-technology Sensing and Transmission Power Optimization

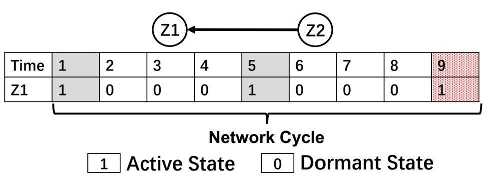


Fig. 5. The WiFi senses the traffic among ZigBee nodes.

1) Cross-technology Sensing: In CTC networks, ZigBee nodes cannot directly inform their working schedules to the WiFi AP due to the huge communication overhead introduced by uplink CTC (i.e., ZigBee to WiFi). To overcome this challenge, we introduce a cross-technology sensing approach to passively sense the working schedules of ZigBee nodes. This approach is based on the fact that the WiFi device can distinguish transmissions from different ZigBee devices by detecting Received Signal Strength (RSS) values even under high interference [12]. In Waves, since a ZigBee node only receives the packets in the active state, the WiFi can sense the transmissions and records the corresponding durations of RSS values. This duration is the active state of the ZigBee node. We note that since multiple devices (i.e., Bluetooth, Baby Monitor, etc) work on the same overlapped channel, the WiFi device may mistakenly record the wrong device. Fortunately, the ZigBee nodes normally have a fixed packet size based on smart applications, which will result in a fixed RSS duration [6]. By checking the RSS duration, the WiFi AP can distinguish the ZigBee packets and know their corresponding applications.

ϕ_i (dB)	5	6	7	9	13	17	20	22
$f(x)$ $(Mbps)$	6	9	12	18	24	36	48	54

TABLE I
An example of the WiFi AP throughput step function.

When successfully sensing the ZigBee transmissions, the WiFi does not need to know which ZigBee node is active. It only needs to record the time information. By repeating this procedure, the recorded time will start to cycle, which is defined as the **Network Cycle**. Therefore, the WiFi AP only needs to conduct WiFi-to-ZigBee transmission during the active states in the network cycle. As shown in Figure 5 at times 1 and 5, $Z2$ transmits packets to $Z1$ during $Z1$'s active state. The WiFi device can sense and record the ZigBee traffic and transmits the time and RSS duration to the WiFi AP. For the WiFi AP, it finds out that every four time slots, a ZigBee node will switch to the active state. Then, the WiFi AP can broadcast the ZigBee packets at time slot 9.

2) Transmission Power Optimization: The objective of transmission power optimization is to conduct communications to the WiFi destination and ZigBee devices at different locations. Since the ZigBee data is embedded within the WiFi traffic, the throughput of the WiFi network should be as high as possible to conduct fast WiFi-to-ZigBee data dissemination. Traditionally, the minimal transmission power $P_{i,min}$ of the WiFi AP to the WiFi device i is determined as:

$$P_{i,min} = PathLoss + P_{threshold} + M_{threshold} \quad (1)$$

where $P_{threshold}$ is the minimum threshold that a packet can be detected by the WiFi client while $M_{threshold}$ is the threshold to prevent packet loss. However, this solution is based on WiFi to WiFi communication. In CTC networks, since the interference generated by ZigBee devices will also affect the WiFi throughput, we need to take ZigBee devices into consideration.

Formally, we denote the interference generated by WiFi and ZigBee devices in the CTC network as $\gamma_i(w)$ and $\gamma_i(z)$, respectively. Then, the SINR ϕ_i for the WiFi AP to a WiFi device i can be calculated as:

$$\phi_i = \frac{P_i g_i}{\gamma_i(w) + \gamma_i(z) + N_0} \quad (2)$$

where P_i is the transmission power from WiFi AP to WiFi device i and g_i is the channel gain. N_0 is the noise at i. Then, the maximum throughput r_i from WiFi AP to the device i can be estimated as $r_i = \psi_i f(10log(\phi_i))$, where ψ_i is the fraction of time for WiFi device i acquiring the wireless channel and $f(10log(\phi_i))$ is the step function of the throughput with different SINR value for a specific WiFi AP (e.g., the step function for CISCO Aironet 1520 is shown in table I [3].) Since it has been shown that the channel access for CSMA protocols are inherently fair [16], [30], assume the time duration of the active state for ZigBee node j is τ_j, then ψ_i can be estimated as:

$$\psi_i \approx \frac{T_c - \sum_0^{n_z} \tau_j}{n_w T_c} + \frac{\sum_0^{n_z} \tau_j}{(n_w + n_z) T_c} \quad (3)$$

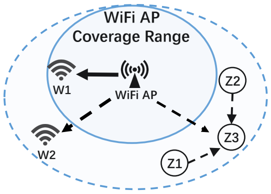


Fig. 6. 1) $Z1$ and $Z2$ can transmit coded packets to $Z3$ when not interfered by the WiFi AP. 2) When the WiFi AP communicates with W2, it simultaneously transmits coded packets to $Z3$

where T_c is the time duration of the network cycle and n_w is the number of WiFi devices. n_z is the number of ZigBee nodes in the current coverage range of the WiFi AP. Finally, the throughput of the WiFi network r_w can be represented as:

$$r_w = \sum_{i}^{n_w} \psi_i f(10log(\phi_i)) \quad (4)$$

As shown in Equation 4, when the transmission power of the WiFi AP is increased, the second term increases. However, since the increase of the transmission power will cover more ZigBee devices (n_z), the first term ψ_i is reduced. Since we cannot predict the WiFi traffic, it is difficult to find the global optimal solution. In Waves, the WiFi AP can try every value larger than $P_{i,min}$ in the predefined step function $f(10log(\phi_i))$ that can achieve highest r_w. This transmission power $P_{i,opt}$ is the local optimal solution, which preserves the WiFi throughput and reduces the ZigBee data dissemination delay at the same time.

The above optimization scheme mainly focuses on the fixed ZigBee working schedule and WiFi modulation scheme. In practice, the ZigBee nodes can change working schedules according to their applications, which may result in the change of network cycle T_c. In addition, since the WiFi transmission power can dynamically change, the WiFi device may suffer a performance drop (e.g., using BPSK or QPSK instead of using 64-QAM) when the transmission power is reduced. In Waves, to maintain the power optimization performance, the WiFi device should conduct cross-technology sensing and update the network cycle (T_c) periodically. Moreover, it is also important to make sure that the minimum threshold $P_{i,min}$ in Equation 1 is determined based on the current modulation scheme.

B. ZigBee Data Dissemination

1) Preliminaries: Fountain codes are widely utilized to achieve reliable communication [28]. Assume there are multiple packets waiting for transmission. The sender will generate an *infinite* number of encoded packets using an XOR process and keep transmitting these coded packets to the receiver. The receiver can decode the original packets by solving linear equations after receiving enough coded packets.

In Waves, we use Luby Transform codes (LT codes) [27] as a specific realization of Fountain codes, which requires low computational resources and can be applied to ZigBee nodes. Traditional approaches require every receiver to receive a sufficient number of coded packets and transmit ACKs back to the sender for transmission termination [15], [13], which cannot be applied to the CTC network. This is because the WiFi device uses 7 overlapped subcarriers to communicate with a ZigBee node, thus transmitting coded packets to all the nodes will significantly reduce the WiFi throughput. To overcome this challenge, we develop a distributed fountain codes transmission technique to improve the data dissemination reliability and preserve the WiFi throughput at the same time.

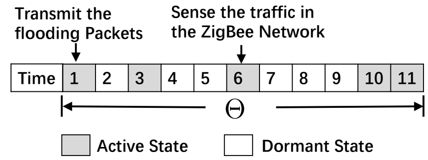


Fig. 7. The WiFi AP broadcasts coded packets at time 1. Then, the WiFi device senses the ongoing ZigBee traffic at time 6.

2) Distributed Fountain Codes Transmission: Intuitively, the WiFi AP should transmit as many coded packets to the ZigBee nodes as possible. However, this solution reduces the throughput of the WiFi network while having little improvements on the data dissemination reliability. As shown in Figure 6, according to the WiFi traffic, after transmitting coded packets to $Z1$ and $Z2$, the WiFi AP starts to communicate with $W1$. Since $Z1$ and $Z2$ are not interfered by the WiFi AP, they can forward coded packets to $Z3$. However, due to the lack of feedbacks from ZigBee nodes, when the WiFi AP is communicating with $W2$, it transmits coded packets to $Z3$ again, which introduces redundant transmissions. Moreover, even if $Z1$ and $Z2$ do not receive enough coded packets, $Z3$ may still successfully decode the coded packets by combining the received packets from $Z1$ and $Z2$ together. Therefore, simply transmitting the coded packets to all the ZigBee nodes neither reduces the data dissemination delay nor improves the data dissemination reliability.

In Waves, the WiFi AP treats the entire ZigBee network as a single ZigBee node with dynamic working schedules. Since the packets are transmitted directly through WiFi, Waves does not care about the topologies of the ZigBee network and receiving status of some specific ZigBee nodes. The data dissemination reliability is unaffected as long as the ZigBee network receives enough packets. Specifically, the WiFi AP will transmit the coded packets according to the active states in the network cycle. The selections of the active state are mainly based on two factors: *i) the time duration of the current WiFi traffic; and ii) the traffic in the ZigBee network.* Formally, for a ZigBee network with N ZigBee nodes, we denote the complete set of the active states during the network cycle as Θ. The active states that receive the coded packets are defined as the **Selected States**.

Based on the WiFi traffic, the WiFi AP can broadcast the coded packets at the time of the nearest active state in the network cycle. Then, this active state will be deleted from the set Θ. Since the WiFi traffic is dynamically changing, the corresponding coverage range of the WiFi AP is also changing. Therefore, for the ZigBee nodes that receive the coded packets, it can transmit the received packets to their neighboring nodes when they are not covered by the WiFi AP. To further reduce the redundant transmissions, WiFi devices will sense the transmissions in the ZigBee network. When ZigBee nodes are forwarding the received packets during its neighboring nodes' active states, these active states in the set Θ will also be deleted, which is shown in Figure 7. This process will continue until all the active states in the set Θ are deleted.

3) Termination of Data Dissemination: In general, the WiFi AP should terminate the data dissemination when Θ is empty. However, due to the unreliable links between WiFi and ZigBee, the ZigBee network may still not receive a sufficient number of coded packets. On the other hand, if the entire network has already received enough packets, the WiFi can conduct early termination to preserve the WiFi throughput. In Waves, the WiFi AP will count the number of transmitted coded packets. If the total number of transmitted packets from the WiFi AP to the ZigBee network does not reach the minimal requirements P_T^{min}, the WiFi AP will continue to transmit the coded packets during the active states in the next network cycle until this lower bound is reached. Otherwise, the WiFi AP can conduct early termination.

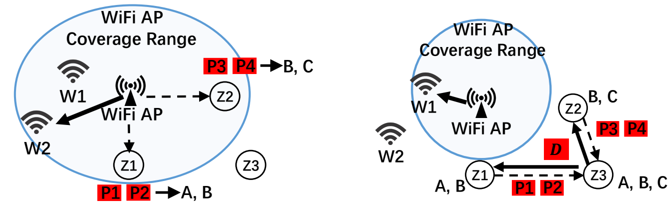
Formally, for a number of K coded packets, the corresponding degree distribution can be represented as $P(d)$. The degree of a coded packet k_j is represented as d_j. The link quality between the WiFi AP and the ZigBee node i is denoted as p_i^w. Assume a number of m packets have been transmitted to the ZigBee node i during its active state. Therefore, the probability $p_r^i(k)$ for a packet to be a redundant coded packet is:

$$p_r^i(d') = \sum_{l=d'}^{d'+\lfloor mp_i^w \rfloor - x} \left(P(l)\frac{\binom{x}{l}\binom{\lfloor mp_i^w \rfloor - x}{l-d'}}{\binom{\lfloor mp_i^w \rfloor}{l}}\right) \qquad (5)$$

where d' is the reduced degree, x is the number of undecoded packets, and ρ is the termination threshold. In other words, when $p_r^i(d') > \rho$, the WiFi AP should stop the transmission. Therefore, the minimum number of transmitted packets P_T^{min} from the WiFi AP to the ZigBee network should satisfy $\mathrm{argmin}_{P_T^{min}} \sum_{i=1}^{P_T^{min}} (\frac{p_r^i(\rho_i)}{P_T^{min}}) > \rho$. When the number of transmitted packets reaches P_T^{min}, the WiFi AP can terminate the transmission. The determination of ρ is tricky. When ρ increases, the data dissemination reliability will be high and the delay will be low. However, it requires the WiFi AP to transmit a higher number of coded packets to the ZigBee network, which sacrifices the WiFi network throughput. Therefore, in practice, the value of ρ should be determined based on the users' applications. Since the WiFi AP does not care which ZigBee node has received the coded packets, ρ does not need to be precisely defined. As long as the whole network receivers enough packets, the data dissemination reliability remains unaffected.

C. Packets Exchange in the ZigBee Network

To cover the whole network and further improve the data dissemination reliability, when receiving the coded packets from the WiFi AP, ZigBee nodes should decode and transmit these packets to its neighboring nodes. Since the neighboring nodes may have already received some of the coded packets from the WiFi AP or other nodes, we use network coding to reduce the number of redundant transmissions.



(a) $Z1$ and $Z2$ receive insufficient number of coded packets from WiFi AP. Each node can only decode two packets.

(b) $Z3$ have received enough packets and can decode A, B and C. Then, it can broadcast one coded packet D to $Z1$ and $Z2$.

Fig. 8. An example of packet exchange in the ZigBee network.

For a node i, if the received data is successfully decoded, it will create random linear combinations of the received packets and then transmit them to its neighboring nodes. Formally, we represent a number of K successfully decoded packets as $\{A_1, A_2, ..., A_K\}$. Then, these packets will be combined together by multiplying a matrix with random values, which is shown as follows:

$$\begin{bmatrix} C_1 \\ \vdots \\ C_K \end{bmatrix} = \begin{bmatrix} a_1 & \cdots & a_K \\ \vdots & \ddots & \vdots \\ k_1 & \cdots & k_K \end{bmatrix} \begin{bmatrix} A_1 \\ \vdots \\ A_K \end{bmatrix} \qquad (6)$$

The node i will keep transmitting the combined packets from C_1 to C_K until receiving acknowledgments from its neighboring nodes. If node i cannot decode the information, it will request the coded packets from its neighboring nodes. As described in section III-B2, even if all its neighboring nodes do not receive enough packets from the WiFi AP, the node i can still decode the information after receiving enough coded packets from its neighboring nodes. In this case, the data dissemination reliability remains unaffected. Moreover, by comparing the packets received from its neighboring nodes, the node i can transmit the missing packets to these nodes during their active states.

If the node i's neighboring nodes have the same working schedule, rather than simply broadcasting the missing packets, the node i can apply the network coding to further reduce the number of redundant transmissions. As shown in Figure 8, assume each ZigBee node requires to receive 3 packets to decode the information. In Figure 8(a), $Z1$ and $Z2$ only receive two coded packets. In Figure 8(b), they transmit the received coded packets to $Z3$. Now, since $Z3$ receives enough packets, it can decode the received packets. Then, based on the transmitted packets from A and B, $Z3$ knows the missing packets of $Z1$ and $Z2$ are C and A, respectively. Then, instead of simply transmitting the missing packets to $Z1$ and $Z2$, $Z3$ only broadcasts the combined packets D, where D can be represented as $D = \alpha_1 A + \alpha_2 C$. α_1 and α_2 are two random values that are indicated in the packet header. By leveraging this approach, Waves can improve the data dissemination reliability with lower number of redundant transmissions.

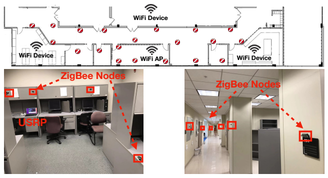


Fig. 9. Smart Office Scenario

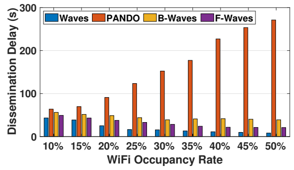


Fig. 10. Dissemination Delay

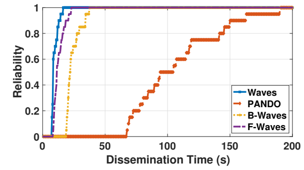


Fig. 11. Dissemination Reliability

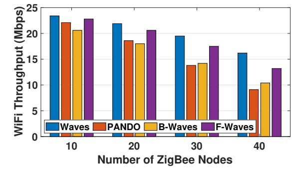


Fig. 12. The WiFi Throughput

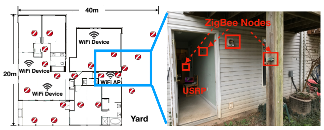


Fig. 13. Smart Home Scenario

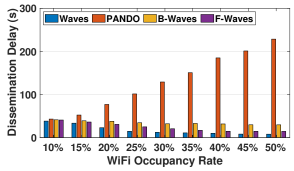


Fig. 14. Dissemination Delay

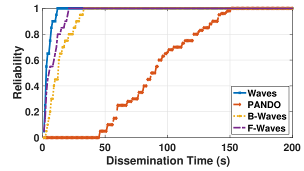


Fig. 15. Dissemination Reliability

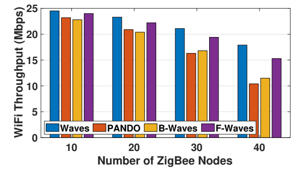


Fig. 16. The WiFi Throughput

	CTC	Fountains codes	ACKs	Network Coding
PANDO	×	✓	×	×
B-Waves	✓	×	×	×
F-Waves	✓	✓	×	×

TABLE II
COMPARISON BETWEEN STATE-OF-THE-ART SOLUTIONS.

IV. IMPLEMENTATION & EVALUATION

A. Experiment Setup

We evaluate Waves under various network settings in smart office and smart home scenarios. We use the existing open source 802.11g [5], [1] to implement the WiFi AP part of Waves on a USRP B210 [7] device. Three additional USRPs are used as WiFi devices to communicate with the WiFi AP. The transmission power of the WiFi AP varies between $1dBm$, $10dBm$, and $20dBm$ according to the distances from the WiFi AP to the WiFi devices. Since the WiFi data will not affect the WiFi to ZigBee communication, we use a stream of '0' as the WiFi traffic. We use Contiki to implement Waves on 20 off-the-shelf ZigBee compliant TelosB nodes. The duty cycles of ZigBee nodes are set as 10%.

Since this is the first work of utilizing the WiFi AP to conduct data dissemination for ZigBee nodes in heterogeneous IoT networks, we can only compare the performance of Waves with the latest data dissemination approach in ZigBee networks PANDO [15] as our baseline. To further show the benefits of our design and conduct fair evaluations, we also implement **Basic Waves (B-Waves)** and **Fountain Waves (F-Waves)**. The comparison between these solutions are listed in table II. Specifically, B-Waves does not apply any coding techniques nor require the ZigBee nodes to transmit ACKs back to the WiFi AP. The main purpose of implementing B-Waves is to understand the disadvantages of physical-level CTC and show the effectiveness of our coding techniques. F-Waves is the advanced version of B-Waves. It utilizes fountain codes to conduct transmissions from WiFi to ZigBee and does not require ACKs from the ZigBee devices. The reason why we implement F-Waves is to show the effectiveness of Waves during the packet exchange process in the ZigBee network.

B. Smart Office Experiments

The smart office scenario mainly contains indoor experiments with relatively high interference (in Figure 9). We first evaluate the average data dissemination delay under different WiFi occupancy rates in Figure 10. All approaches show relatively low data dissemination delay when the WiFi occupancy rate is as low as 10%. However, with the increase in the WiFi traffic, the delay of Waves decreases quickly while the delay of PANDO increases rapidly. When the WiFi occupancy rate reaches 50%, the average delay of Waves is $8.1s$, which is around ***33.5 times*** faster than that of PANDO ($271.3s$). This is because Waves can leverage the ongoing WiFi traffic to conduct WiFi-to-ZigBee communication while PANDO suffers high interference from the WiFi traffic. The performance of Waves is around 4.5 times better than that of B-Waves. This is because Waves utilizes distributed fountain codes transmissions to improve the data dissemination reliability and the packet exchange process of Waves is faster than other approaches. The performance of F-Waves is around 2.4 times worse than that of Waves. This is because the packet exchange processes of F-Waves is inefficient, which reduces the overall data dissemination delay.

Figure 11 shows the reliability progress when the WiFi occupancy rate is 35%. For Waves, more than 80% of the ZigBee nodes finish the data dissemination within $20s$ and the average delay is around $23s$. For B-Waves and F-Waves, the average delays are around $43s$ and $25s$, respectively. This is because the WiFi AP in Waves can change its transmission power to reach the ZigBee nodes at different distances, which avoids the delay introduced by multi-hop transmissions. In contrast, PANDO is struggling to conduct data dissemination in the first $70s$. This is because PANDO is not designed for CTC networks. It treats the WiFi traffic as interference. Therefore, due to the high WiFi occupancy rate, it is difficult for the sender to perform data dissemination. Moreover, the silence feedback scheme in PANDO only works under low CTI, which further reduces the network performance. As packets reach the ZigBee nodes that far from the WiFi AP, it is less possible that the transmissions are interfered by the WiFi traffic. As a result, the average delay of PANDO is $185s$, which is around ***9 times*** slower than Waves.

Figure 12 shows the impact on WiFi throughput under different network densities. The WiFi throughput of Waves remains the highest among the state-of-the-art solutions. When

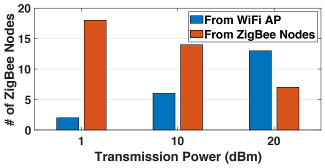


Fig. 17. Contribution of the WiFi AP vs. WiFi AP Transmission Power

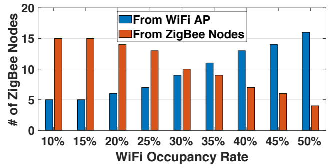


Fig. 18. Contribution of the WiFi AP vs. WiFi Traffic

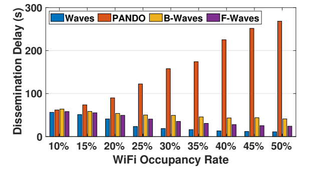


Fig. 19. Dissemination Delay (Smart Office)

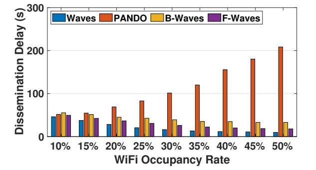


Fig. 20. Dissemination Delay (Smart Home)

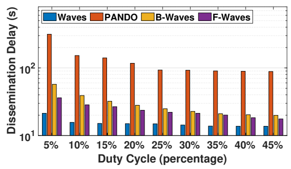


Fig. 21. Dissemination Delay (Smart Office)

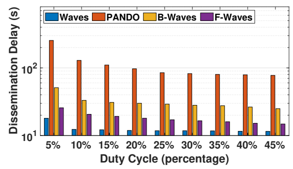


Fig. 22. Dissemination Delay (Smart Home)

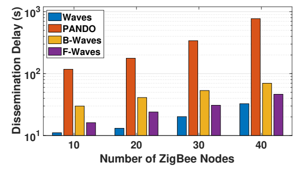


Fig. 23. Dissemination Delay (Smart Office)

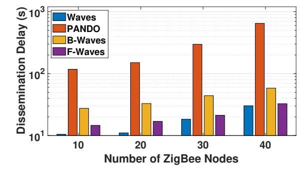


Fig. 24. Dissemination Delay (Smart Home)

the number of ZigBee nodes reaches 40, the throughput of Waves is 1.81***,*** 1.67 ***and*** 1.22 ***times*** better than that of PANDO, B-Waves and F-Waves, respectively. This is because the WiFi-to-ZigBee communication and packet exchange process in Waves are much more efficient than those of the state-of-the-art solutions. For PANDO, the WiFi must frequently back off according to the CSMA scheme. Since B-Waves sacrifices part of the WiFi subcarriers for CTC while the communication reliability is still low, the performance of B-Waves is the worst.

C. Smart Home Experiments

The smart home scenario contains both indoor and outdoor experiments (in Figure 13). Specifically, the WiFi AP is deployed inside the home while the ZigBee nodes are deployed both inside and outside the smart home. As shown in Figure 14, the average delay of Waves is much than that of PANDO, B-Waves and F-Waves. When the WiFi occupancy rate is 10%, the delay of Waves is slightly better than PANDO, B-Waves and F-Waves. As the WiFi traffic increases to 50%, the average delay of Waves is around 27.5***,*** 3.5 ***and*** 1.74 ***times*** better than that of PANDO, B-Waves and F-Waves, respectively.

As shown in Figure 15, the data dissemination process of Waves shows the advantage of our design. 80% of the ZigBee nodes still receive the packets within $20s$. The dissemination processes of PANDO, B-Waves and F-Waves are smoother when compared to Figure 11. This is because the interference in smart home is lower than in the smart office. For PANDO, it can transmit coded fountain codes and terminate transmissions easier. For B-Waves and F-Waves, they also can easily exchange the received packets in this scenario. Figure 16 shows the WiFi throughput in the smart home scenario. Similar to the Smart Office scenario, the performance of Waves is much better than that of other solutions. As the number of ZigBee nodes reaches 40, the performance of Waves is around 1.72, 1.55 and 1.16 times better than PANDO, B-Waves and F-Waves, respectively.

D. System Insight Analysis

In this section, we explain why Waves has better performance by revealing some system insights. Since the smart office and smart home scenarios have the same trend, we only show the evaluation results in the smart home scenario.

Figure 17 depicts the number of ZigBee nodes that receive the coded packets from the WiFi AP directly under different transmission power constraints. When the transmission power is set to $1dBm$, only a small number of ZigBee nodes can receive packets from the WiFi AP directly and most of the data dissemination packets are exchanged through the ZigBee network. As transmission power increases, the data dissemination packets can be directly transmitted to a larger number of ZigBee nodes. ***Insight:*** *Waves can leverage the WiFi AP adaptive power control to reach the nodes that are far from the WiFi AP, which reduces the delay introduced by multi-hop transmissions.*

Figure 18 shows the number of ZigBee nodes that directly receive the packets from the WiFi AP under different WiFi occupancy rates. When the WiFi occupancy rate is 10%, only a small number of ZigBee devices receive packets directly from the WiFi AP. This is because the interference from the WiFi traffic is low and has little impact on the ZigBee network. When the WiFi Occupancy rate reaches 50%, a larger number of ZigBee nodes have to frequently back off. In this case, the WiFi AP directly performs data dissemination to these nodes to reduce the data dissemination delay. ***Insight:*** *Waves can dynamically change the transmissions from WiFi AP to the ZigBee nodes to reduce the average delay.*

E. System Sensitivity Analysis

1) Mobility: Figure 19 and Figure 20 show the average delay when WiFi devices are moving at $1m/sec$. To achieve the desired speed accurately, we implement the WiFi device on a DJI robot master platform [2]. As we can see from these figures, Waves still shows the best performance while PANDO performs better under the mobility scenario when the WiFi occupancy rate is low. This is because the CTI is lower as WiFi devices move away, which enables the transmissions in the ZigBee network. On the contrary, B-Waves performs worst when the WiFi occupancy rate is 10%. This is because B-Waves cannot conduct reliable WiFi to ZigBee communication. It requires ZigBee nodes to frequently exchange the received packets in the ZigBee network, which increases the data dissemination delay.

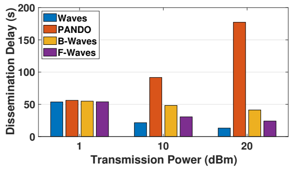


Fig. 25. Dissemination Delay (Smart Office)

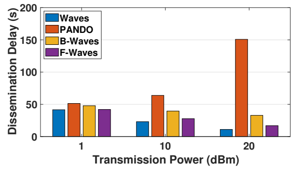


Fig. 26. Dissemination Delay (Smart Home)

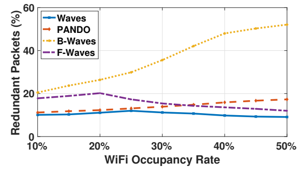


Fig. 27. Percentage of Redundant Packets (Smart Office)

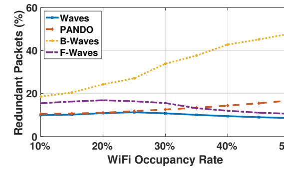


Fig. 28. Percentage of Redundant Packets (Smart Home)

2) Duty Cycles: The average data dissemination delay under different ZigBee duty cycles are shown in Figure 21 and Figure 22. Waves shows great advantages under different duty cycles. When the duty cycle is as low as 5%, the average delay of Waves ($21.32s$ smart office and 18.03 smart home) is around ***14.1 times*** better than PANDO ($314.6s$ smart office and $254.1s$ smart home). This is because the transmissions in PANDO not only interfere with the WiFi traffic but suffer multihop transmission delays. As the duty cycle increases, the delay of PANDO reduces rapidly ($88.48s$ smart office and 25.01 smart home) while the performance of Waves almost remains the same ($13.72s$ smart office and $11.53s$ smart home). For B-Waves and F-Waves, due to the inefficiency of the packet exchange process, the average delays are around 2.60 ***times and*** 1.31 ***times*** worse than that of Waves.

3) Network Densities: Figure 23 and Figure 24 show the average delay under different network densities. During the experiment, the WiFi occupancy rate is set to 35%. As shown in these figures, the delays of Waves and PANDO increase at different speeds. This is because the data dissemination in PANDO is conducted by a single ZigBee source while multiple ZigBee nodes in Waves can exchange the received packets. The delays of B-Waves and F-Waves are also increasing faster than those of Waves due to the unreliability and redundancy introduced during the data dissemination process. When the number of ZigBee nodes reaches 40, the average delay of Waves is around 22***,*** 2.1***, and*** 1.4 ***times*** less than those of PANDO, B-Waves and F-Waves, respectively.

4) WiFi AP Transmission Power: Figure 25 and Figure 26 show the average delay under different WiFi AP power restrictions. When the transmission power is as low as $1dBm$, the WiFi AP only covers a small area. In this case, a limited number of ZigBee nodes can receive the packets from the WiFi AP. Meanwhile, only the ZigBee nodes that are close to the WiFi AP are affected by the WiFi traffic. Therefore, the average delays of Waves, PANDO, TwinBee, B-Waves and F-Waves are almost the same. As the transmission power increases, more ZigBee nodes can be reached by the WiFi AP and the corresponding delay reduces rapidly. However, since PANDO is not designed for high CTI, a large number of ZigBee nodes in PANDO are interfered with WiFi devices, which significantly hampers the data dissemination process.

5) Message Overhead: We study the message overhead in Figure 27 and Figure 28. The smart office and smart home scenarios show the same trend. When the WiFi occupancy rate is 10%, the percentage of redundant packets introduced by PANDO and Waves are almost the same. B-Waves has the highest overhead, which is introduced by the ZigBee-to-WiFi ACKs and redundant packet exchange in the ZigBee network. Counterintuitively, the overhead of Waves and F-Waves are reduced as the WiFi occupancy rate reaches 50%. This is because most of the ZigBee nodes can receive the packets through the WiFi AP. Therefore, the overhead is mainly introduced by fountain codes. As a result, when the WiFi Occupancy rate reaches 50%, the performance of Waves is around 1.9, 5.6, and 1.3 times better than that of PANDO, B-Waves and F-Waves, respectively.

V. Discussions

I. Impact of different WiFi standards. In Waves, although the WiFi device mainly utilizes 802.11g to perform CTC, the overall performance of WiFi devices will not be affected by other WiFi standards (i.e., 802.11e or 802.11n). This is because the CTC physical layer emulation techniques do not change the WiFi physical layer. It only requires the WiFi device to emulate the ZigBee signal by controlling the payload of a WiFi packet. Since the ZigBee device occupies a 2MHz band, only the overlapped 7 WiFi subcarriers are used to emulate the ZigBee signal.

For the 802.11e, it mainly focuses on the MAC layer enhancement, which does not change the physical layer of the WiFi device. Therefore, the performance of Waves remains unaffected. For the 802.11n, it utilizes OFDM modulation to conduct communication, which is similar to 802.11g. The only difference is that the 802.11n applies OFDM on a 40MHz channel and the number of data-carrying subcarriers increases to 114. However, since the ZigBee device occupies a 2MHz band, the WiFi device still utilizes the same 7 subcarriers to conduct the WiFi to ZigBee communication. Therefore, the performance of Waves remains unaffected.

II. Impact of multiple WiFi APs. In Waves, although we mainly focus on the single WiFi AP network, the proposed scheme can be extended to the network with multiple WiFi APs. This is because we did not change the WiFi physical layer and MAC layer. For multiple WiFi APs, they can utilize the existing CSMA scheme to avoid the interference between each other. Moreover, for the ZigBee node that is currently out-of the coverage range of a single WiFi AP, the WiFi AP can transmit the data to its neighboring APs and ask those WiFi APs to conduct the data dissemination.

III. Impact of out-of-range ZigBee nodes. In Waves, the WiFi AP leverages the physical-level CTC to conduct data dissemination to the ZigBee network. To mitigate the interference and increase the coverage range, we introduce the WIDB scheme, which enables the WiFi device to effectively control its transmission power to reach the ZigBee nodes at different distances. In addition, the ZigBee nodes can also receive the coded packets from its neighboring nodes during the packet exchange process in the ZigBee network, which improves the data dissemination reliability.

IV. The data dissemination reliability. In this work, the WiFi device only needs to transmit a limited number of coded packets to the ZigBee network. The ZigBee nodes can exchange the received packets if they cannot decode the data. This approach can guarantee approximately 100% reliability in most cases. However, if the ZigBee nodes have aperiodic transmissions, the data dissemination reliability will be affected. This is because the cross-technology sensing scheme requires the WiFi device to understand the network cycle. If a ZigBee device is conducting aperiodic transmissions, the WiFi device will mistakenly consider a single ZigBee nodes as multiple nodes, which will result in broadcasting the data to the same ZigBee node multiple times. Moreover, without the accurate network cycle, the WiFi device cannot control its transmission power precisely, which reduces the data dissemination reliability. To overcome this challenge, the ZigBee node with aperiodic transmissions has to leverage packet-level CTC to inform the WiFi device of its working schedules. However, as mentioned in section III-A1, this packet-level CTC will increase the network overhead.

V. The deployment of Waves. Waves only requires the software-level changes to be deployed to the WiFi and ZigBee coexistence networks. Specifically, the WiFi adaptive power control utilized in Waves is defined in the IEEE 802.11 standard while the physical-level CTC techniques only require the WiFi device to control its payload to support the WiFi-to-ZigBee communication. In Waves, we also utilize coding techniques to improve the data dissemination reliability and reduce the network overhead. However, these techniques do not require hardware modificantions for WiFi and ZigBee devices, which reduces the deployment requirements for Waves.

VI. Related Work

I. Cross-technology Communication has been proposed to support seamless, gateway-free communications among heterogeneous IoT radios [8], [42], [24]. Recently, researchers have developed several techniques to enable simultaneous communication among multiple heterogeneous IoT devices. EMF [9] is able to realize communication between ZigBee and WiFi simultaneously by shifting the packet transmission order. B^2W^2 [10] achieves N-way simultaneous communication between WiFi and Bluetooth devices. Since these approaches use packet level CTC, they can only achieve low throughput. The physical layer CTC technique WEBee [26] achieves high throughput communication from WiFi to ZigBee by using a small number of WiFi subcarriers (that are overlapped with ZigBee) to emulate ZigBee packets. PMC [11] demonstrates that the non-overlapped WiFi subcarriers can also be utilized to transmit traditional WiFi data. Therefore, a WiFi device can conduct parallel WiFi-to-WiFi and WiFi-to-ZigBee communications by using a single WiFi data stream. Building on the top of the recent advances in CTC techniques, we design Waves, which utilizes WiFi AP to initiate data dissemination for ZigBee nodes. By enabling simultaneous WiFi-to-WiFi and WiFi-to-ZigBee communication, Waves can significantly reduce the data dissemination delay. Moreover, since Waves does not require modification in the hardware, which has potential to be applied to commodity devices.

II. Data Dissemination has been applied to numerous networks and applications [31], [41], [44], [25]. Opportunistic Flooding [20] mainly utilizes delay distribution to reduce the delay and redundancy in low-duty-cycle wireless sensor networks. A wireless link-correlation feature [36] has also been widely investigated to conduct efficient data dissemination [38], [43], [21]. For example, Collective Flooding [43] and Correlated Flooding [21] explore the link correlation to reduce the redundant transmissions and reduce the dissemination delay. Constructive interference has also been utilized to improve the data dissemination performance [39], [40], [18], [17]. Splash [14] achieves reliable data dissemination with low latency by exploiting constructive interference and channel diversity. Other data dissemination techniques [22], [15] leverage the coding techniques. Rateless Deluge [22] utilizes rateless codes to improve the transmission reliability over regular Deluge. The most recent technique – Pando [15] improves the performance of Deluge by using the combination of LT codes and pipelining. Although data dissemination has been extensively investigated, prior approaches mainly focus on improving the data dissemination performance within the same network (i.e., WiFi or ZigBee network). Little work has been conducted to investigate how to leverage CTC in heterogeneous IoT networks for further performance improvement, especially when the number of IoT devices is exponentially increasing. Instead of treating the IoT devices from other networks (e.g., WiFi) as interference and harmful, our work is the first work that explores how to leverage the WiFi AP as a collaborative and benign device to conduct data dissemination in the ZigBee network, which proceeds to become more and more common nowadays.

VII. Conclusion

The exponentially increasing number of IoT devices and recent advances in CTC physical layer design motivates us to investigate how to leverage the CTC technique for further performance improvements in heterogeneous IoT networks. In this paper, we introduce Waves, which seamlessly enables the simultaneous WiFi-to-WiFi communication and ZigBee data dissemination. We extensively evaluated Waves under different settings. Evaluation results indicate that Waves can achieve reliable and fast data dissemination. With the support of the latest CTC technologies, Waves has the potential to be deployed on commodity devices. Moreover, Waves opens a new direction for collaborative network layer design for heterogeneous IoT networks.

VIII. Acknowledgement

This project is partially supported by NSF grants CNS-1652669 and CNS-1824491.

REFERENCES

[1] https://github.com/bastibl/gr-ieee802-11.
[2] https://www.dji.com/robomaster-s1.
[3] https://www.cisco.com/c/en/us/td/docs/wireless/technology/mesh/7-3/design/guide/Mesh.html.
[4] 802.11, I. Part 11: Wireless lan medium access control (mac) and physical layer (phy) specifications.
[5] 802.11G. http://infocom.uniroma1.it/alef/802.11/standard/802.11g-2003.pdf.
[6] ACAR, A., FEREIDOONI, H., ABERA, T., SIKDER, A. K., MIETTINEN, M., AKSU, H., CONTI, M., SADEGHI, A.-R., AND ULUAGAC, A. S. Peek-a-boo: I see your smart home activities, even encrypted!
[7] B210, U. https://www.ettus.com/product/category/USRP-Bus-Series.
[8] CHEBROLU, K., AND DHEKNE, A. Esense: Communication through energy sensing. In *MobiCom* (2009).
[9] CHI, Z., HUANG, Z., YAO, Y., XIE, T., SUN, H., AND ZHU, T. Emf: Embedding multiple flows of information in existing traffic for concurrent communication among heterogeneous iot devices. In *INFOCOM* (2017).
[10] CHI, Z., LI, Y., SUN, H., YAO, Y., LU, Z., AND ZHU, T. B2w2: N-way concurrent communication for iot devices. In *SenSys* (2016).
[11] CHI, Z., LI, Y., YAO, Y., AND ZHU, T. Pmc: Parallel multi-protocol communication to heterogeneous iot radios within a single wifi channel. In *ICNP* (2017).
[12] CHI, Z., YAO, Y., XIE, T., LIU, X., HUANG, Z., WANG, W., AND ZHU, T. Ear: Exploiting uncontrollable ambient rf signals in heterogeneous networks for gesture recognition. In *Proceedings of the 16th ACM Conference on Embedded Networked Sensor Systems* (2018).
[13] DIMAKIS, A. G., PRABHAKARAN, V., AND RAMCHANDRAN, K. Distributed fountain codes for networked storage. In *ICASSP* (2006).
[14] DODDAVENKATAPPA, M., CHAN, M. C., LEONG, B., ET AL. Splash: Fast data dissemination with constructive interference in wireless sensor networks. In *NSDI* (2013).
[15] DU, W., LIANDO, J. C., ZHANG, H., AND LI, M. When pipelines meet fountain: Fast data dissemination in wireless sensor networks. In *ACM SenSys* (2015).
[16] DURVY, M., AND THIRAN, P. A packing approach to compare slotted and non-slotted medium access control. In *Infocom 2006* (2006).
[17] FERRARI, F., ZIMMERLING, M., MOTTOLA, L., AND THIELE, L. Low-power wireless bus. In *SenSys* (2012).
[18] FERRARI, F., ZIMMERLING, M., THIELE, L., AND SAUKH, O. Efficient network flooding and time synchronization with glossy. In *Information Processing in Sensor Networks (IPSN), 2011 10th International Conference on* (2011).
[19] GANDARILLAS, C., MARTÍN-ENGEÑOS, C., POMBO, H. L., AND MARQUES, A. G. Dynamic transmit-power control for wifi access points based on wireless link occupancy. In *2014 IEEE Wireless Communications and Networking Conference (WCNC)* (2014).
[20] GUO, S., HE, L., GU, Y., JIANG, B., AND HE, T. Opportunistic flooding in low-duty-cycle wireless sensor networks with unreliable links. In *IEEE Transactions on Computers* (2014).
[21] GUO, S., KIM, S. M., ZHU, T., GU, Y., AND HE, T. Correlated flooding in low-duty-cycle wireless sensor networks. In *Proceedings of the 2011 19th IEEE International Conference on Network Protocols* (2011), ICNP.
[22] HAGEDORN, A., STAROBINSKI, D., AND TRACHTENBERG, A. Rateless deluge: Over-the-air programming of wireless sensor networks using random linear codes. In *IPSN* (2008).
[23] INSTRUMENTS, T. https://www.ti.com/lit/ds/symlink/cc2420.pdf.
[24] KIM, S. M., AND HE, T. Freebee: Cross-technology communication via free side-channel. In *MobiCom* (2015).
[25] LI, S., SU, L., SULEIMENOV, Y., LIU, H., ABDELZAHER, T., AND CHEN, G. Centaur: Dynamic message dissemination over online social networks. In *ICCCN* (2014).
[26] LI, Z., AND HE, T. Webee: Physical-layer cross-technology communication via emulation. In *MobiCom* (2017).
[27] LUBY, M. Lt codes. In *Foundations of Computer Science* (2002).
[28] MACKAY, D. J. Fountain codes.
[29] MARÓTI, M., KUSY, B., SIMON, G., AND LÉDECZI, Á. The flooding time synchronization protocol. In *SenSys* (2005).
[30] MHATRE, V. P., PAPAGIANNAKI, K., AND BACCELLI, F. Interference mitigation through power control in high density 802.11 wlans. In *IEEE INFOCOM 2007-26th IEEE International Conference on Computer Communications* (2007).
[31] MOTTOLA, L., PICCO, G. P., CERIOTTI, M., GUN?, Ş., AND MURPHY, A. L. Not all wireless sensor networks are created equal: A comparative study on tunnels. In *TOSN* (2010).
[32] NITHYA, V., RAMACHANDRAN, B., AND MURUGANAND, K. Energy conservation in ieee 802. 15. 4 compliant wireless sensor network using lt codes. In *International Journal of Computer Applications, 2013.*
[33] QIAO, D., CHOI, S., JAIN, A., AND SHIN, K. Adaptive transmit power control in ieee 802.11a wireless lans. In *The 57th IEEE Semiannual Vehicular Technology Conference* (2003).
[34] QIAO, D., CHOI, S., JAIN, A., AND SHIN, K. Miser: An optimal low-energy transmission strategy for ieee 802.11a/h. In *MobiCOM* (2003).
[35] QIAO, D., CHOI, S., AND SHIN, K. Interference analysis and transmit power control in ieee 802.11a/h wireless lans. In *IEEE/ACM Transactions on Networking* (2007).
[36] SRINIVASAN, K., JAIN, M., CHOI, J. I., AZIM, T., KIM, E. S., LEVIS, P., AND KRISHNAMACHARI, B. The κ factor: inferring protocol performance using inter-link reception correlation. In *MobiCom* (2010).
[37] SUN, L., DENG, H., SHESHADRI, R. K., ZHENG, W., AND KOUTSONIKOLAS, D. Experimental evaluation of wifi active power/energy consumption models for smartphones. *IEEE Transactions on Mobile Computing* (Jan 2017).
[38] WANG, S., KIM, S. M., LIU, Y., TAN, G., AND HE, T. Corlayer: A transparent link correlation layer for energy efficient broadcast. In *Proceedings of the 19th annual international conference on Mobile computing & networking* (2013).
[39] WANG, Y., HE, Y., MAO, X., LIU, Y., AND LI, X.-Y. Exploiting constructive interference for scalable flooding in wireless networks. In *IEEE/ACM Transactions on Networking* (2013).
[40] WHITEHOUSE, K., WOO, A., JIANG, F., POLASTRE, J., AND CULLER, D. Exploiting the capture effect for collision detection and recovery. In *EmNetS-II* (2005).
[41] ZHANG, X., AND SHIN, K. G. Chorus: Collision resolution for efficient wireless broadcast. In *INFOCOM* (2010).
[42] ZHANG, Y., AND LI, Q. Howies: A holistic approach to zigbee assisted wifi energy savings in mobile devices. In *INFOCOM* (2013).
[43] ZHU, T., ZHONG, Z., HE, T., AND ZHANG, Z.-L. Exploring link correlation for efficient flooding in wireless sensor networks. In *USENIX NSDI* (2010).
[44] ZÚÑIGA, M., AND KRISHNAMACHARI, B. Optimal transmission radius for flooding in large scale sensor networks. *Cluster Computing* (2005).