CIRF: Constructive Interference-based Reliable Flooding in Asynchronous Duty-Cycle Wireless Sensor Networks

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***Abstract*—Flooding is one of the most fundamental functions in wireless sensor networks (WSNs) and has been investigated extensively. Existing flooding schemes in duty-cycle WSNs can be categorized into two categories: synchronous ones and asynchronous ones. In practice *asynchronous* schemes are preferable since synchronous ones introduce more complexity and overhead for necessary clock synchronization. Existing asynchronous approaches are however imperfect for reliable flooding in duty-cycle WSNs. For example, opportunistic flooding is less flexible and Asynchronous Duty-cycle Broadcasting (ADB) suffers unsatisfactory flooding latency. We propose Constructive Interference-based Reliable Flooding (CIRF) in this paper, a novel design for reliable flooding in asynchronous duty-cycle WSNs. CIRF is integrated with the MAC protocol Receiver-Initiated MAC (RI-MAC) to improve the utilization of wireless medium and guarantee one-hop reliable transmission. The key idea of CIRF is to exploit the constructive interference feature when concurrent transmission occurs, which can be common in RI-MAC based WSNs. Simulation results indicate that CIRF achieves reliable flooding with reduced flooding latency, higher energy efficiency and delivery ratio compared to existing schemes.**

***Index Terms*—Wireless Sensor Networks, Asynchronous, Flooding, Constructive Interference, RI-MAC.**

I. Introduction

Wireless sensor networks (WSNs) have been used for many long-term applications such as environment monitoring [1] and infrastructure protection [2]. Sensor nodes are generally powered by battery. They can neither be replaced nor recharged due to environmental constraints. Therefore, WSNs usually operate in duty-cycle mode to save the limited energy supply. Every node turns its radio on periodically with duty-cycling, alternating between active and dormant states.

Flooding is a fundamental service in WSNs. It is used for time synchronization [3], data dissemination [4], node localization [5], and other applications [6]. The main objective of network flooding is to deliver packets from a source node (the sink node) to all others reliably and rapidly.

Existing flooding schemes in duty-cycle WSNs can be divided into two categories: synchronous ones and asynchronous ones. Synchronous approaches [7], [8] require clock synchronization among neighboring nodes, which introduces extra complexity and overhead. Asynchronous approaches include opportunistic flooding [9], ADB [10] and Flash [11]. However, opportunistic flooding lacks flexibility, the flooding latency of ADB is not satisfactory and Flash suffers the scalability problem.

In asynchronous duty-cycle WSNs, network flooding encounters several challenges. First, flooding in an asynchronous duty-cycle WSN is usually achieved through a number of unicasts since nodes wake up independently. This kind of flooding is very costly. Second, data transmission can get lost since wireless link is unreliable especially for low-power embedded devices [12]. ARQ (Automatic Repeat reQuest)-based mechanism is thus usually needed to guarantee the one-hop reliability.

To overcome the challenges above, we propose a novel Constructive Interference-based Reliable Flooding (CIRF) for reliable flooding in asynchronous duty-cycle WSNs. CIRF is integrated with the MAC protocol RI-MAC [13], which can not only improve the utilization of wireless channels, but also implement ARQ by its acknowledgment beacon (ACK) naturally. CIRF exploits the constructive interference [14], [15] feature of concurrent transmissions which can be very common in RI-MAC based WSNs. Constructive interference can greatly improve the reliability of packet transmission in WSNs with unreliable links, thus reducing energy consumption and flooding delay.

The contributions of this work are as follows:

- To the best of our knowledge, CIRF is the first work based on constructive interference for reliable flooding in asynchronous duty-cycle WSNs based on RI-MAC. CIRF can exploit many chances of concurrent transmission produced by the underlying RI-MAC.
- CIRF efficiently avoids redundant transmissions and improves Packet Reception Rate (PRR) at the same time, thus decreasing not only energy cost, but also flooding latency. Additionally it achieves high and stable delivery ratio regardless of changes in the density or duty cycle of networks since it can make use of the accumulation effect of different links.
- We evaluate CIRF by extensive simulations. Results indicate that CIRF outperforms ADB, opportunistic flooding and RI-MAC in terms of energy efficiency, flooding latency and delivery ratio.

The remainder of this paper is organized as follows. We review the related works in Section II. Section III presents the

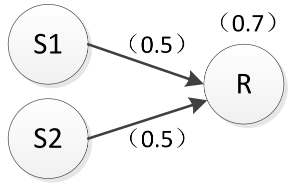


Fig. 1. Effect of constructive interference.

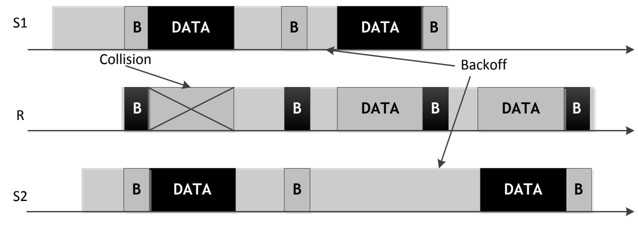


Fig. 2. Backoff in RI-MAC.

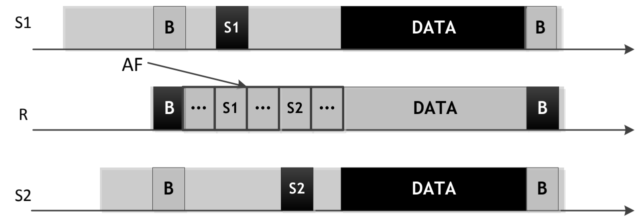


Fig. 3. Overview of CIRF.

network model and assumptions. In Section IV we describe the detailed CIRF design. Evaluation results are presented in Section V. Finally, we conclude this paper in Section VI.

II. Related Work

As an essential operation in WSNs, flooding has been extensively studied. Existing flooding schemes in duty-cycle WSNs can be roughly divided into synchronous ones and asynchronous ones.

Guo $et\ al.$ propose Correlated Flooding [7] in low-duty-cycle WSNs, in which high correlated nodes receive packets simultaneously and reply with a single ACK. Cheng $et\ al.$ propose dynamic switching-based flooding [8] in low-duty-cycle WSNs. It effectively reduces flooding latency and energy cost through dynamic switching decision making when encountering a transmission failure. They however both realize flooding through synchronous methods which need costly time synchronization. Unlike [7] and [8], the scheme we proposed in this paper (CIRF) realizes flooding in an asynchronous way.

Guo $et\ al.$ propose an energy optimal tree based Opportunistic Flooding [9] for WSNs with unreliable wireless links and asynchronous working schedules. Based on the delay distribution along a flooding tree, it makes a probabilistic forwarding decision at each sender. The scheme proposed in [9] is however only suitable for the scenario that the working schedules of sensor nodes are fixed and is less flexible. Sun $et\ al.$ propose ADB [10], a multihop broadcast protocol for asynchronous duty-cycle WSNs. ADB avoids redundant transmissions and transmissions over poor links with extra footer appended to data and ACKs indicating broadcast progress. But [10] suffers unsatisfactory long delay. Our proposed scheme CIRF further exploits the accumulation effect of poor links in the network and achievers higher delivery ratio compared to ADB. Flash [11] uses the capture effect to allow concurrent transmissions among neighboring nodes, achieving rapid network flooding in WSNs. In contrast, we use the emerging technique of constructive interference, which is different from the capture effect and from the traditional harmful interference (e.g., [16]). Constructive interference, however, should be used carefully, otherwise, the packet reception performance may degrade as the node density or the size of the network increases [15].

III. Preliminaries

In this section, we describe the network model and assumptions related to the CIRF design.

A. Network Model

We consider a WSN with N nodes deployed in a given field. Each node is duty-cycled with two possible states, the active state and the dormant state, switched according to its own working schedule. Specifically, a duty-cycle interval T is equally divided into several time units τ, and each node randomly chooses one of them as its active state.

In order to improve the efficiency of the wireless channel, we choose receiver-initiated MAC protocol, RI-MAC [13] in CIRF. Each node announces its wake-up with a beacon packet. A transmitter starts data transmission upon receiving a beacon from its intended receiver, and then waits for an ACK from the receiver. After receiving a DATA packet, a node will keep active until all of its neighbors have received this packet to guarantee reliability and reduce flooding latency.

B. Constructive Interference

Constructive interference originates from the scenario that multiple transmitters send an identical packet to a common receiver simultaneously. Constructive interference potentially allows orders of magnitude reductions in energy consumptions and improvements on link quality. Let $p_{i\to j}$ denote the PRR from node i to node j. As shown in Figure 1, $p_{S1\to R} = 0.5$, $p_{S2\to R} = 0.5$, when $S1$ and $S2$ transmit packet to R simultaneously, the PRR of R reaches 0.7.

Constructive interference has a precondition that the maximum temporal displacement Δ of concurrent transmissions should be less than a threshold. This threshold equals to $0.5\mu s$ for IEEE 802.15.4 radio [15]. In reality, Triggercast [17], a distributed middleware, has been proposed to generate constructive interference in TMote Sky sensor nodes. It is demonstrated that Triggercast provides on average 1.3×PRR performance gains.

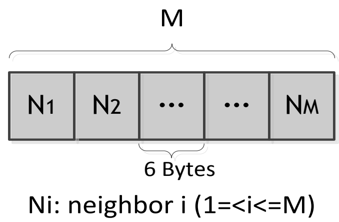


Fig. 4. AF structure.

C. Link Quality Estimation

Wireless communication in WSNs is unreliable due to many factors such as interference, attenuation, and channel fading. We assume that the MAC layer provides the link quality estimation service. There has been many existing work on how to measure wireless link quality efficiently and accurately [18].

IV. Main Design of CIRF

In this section, we describe the design of CIRF. We present the details after an overview of CIRF.

A. Overview

It is common that more than one node waits for the same neighbor to wake up when flooding in an asynchronous duty-cycle WSN where RI-MAC is adopted. In original RI-MAC protocol, contending transmitters cause collision and backoff mechanism is used for several retransmissions. As shown in Figure 2, after R wakes up and sends a beacon, $S1$ and $S2$ transmit DATA packet immediately, which results in collision inevitably. Then backoff is adopted for $S1$ and $S2$ to retransmit DATA packet separately. Backoff however causes unnecessary retransmissions and finally results in high energy cost and long flooding latency since DATA packets are identical in one flooding cycle.

We exploit the constructive interference feature of concurrent transmissions to deal with the above problem. In CIRF, constructive interference is leveraged to avoid redundant transmissions and improve PRR of the receiver when several transmitters wait for a common receiver. Figure 3 gives an overview of the operation of CIRF. After receiving beacon from R and waiting for a certain period, $S1$ and $S2$ transmit DATA packet simultaneously at the data frame period.

A node does not go to sleep until all of its neighbors have received current packet in reliable flooding. But the receiver can not distinguish the transmitters from DATA packet, i.e., the neighbors that have already received the packet when constructive interference is introduced. So extra information need to be exchanged in the transmission procedure.

B. Details

1) Afore-Frame Assignment: Every time a node wakes up and receives a DATA packet, it must know which neighbors have received this packet and which ones have not. It goes to sleep as soon as all its neighbors have received this packet.

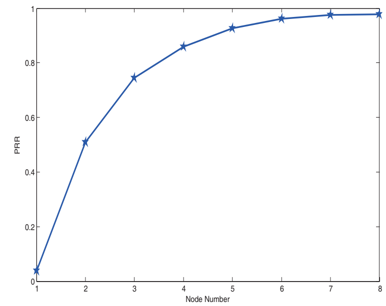


Fig. 5. PRR versus node number.

To notify the receiver of transmitter's information, we add an Afore-Frame (AF) in RI-MAC process. This frame is composed of M slots (The value of M will be discussed later), each slot assigned to one of its neighbors. The length of a slot is just the same as a base beacon in RI-MAC, 6 bytes accordingly. Figure 4 describes the AF structure.

In the neighbor discovery phase, each node broadcasts a hello message and receives messages from neighbors. After collecting all hello messages, node determines its AF length M and the neighbors sequence in the AF. Then it broadcasts this information with another message. After receiving the second message from a neighbor, node records the neighbor's ID, its AF length and the order of itself in the AF.

2) Constructive Interference Transmission: After a receiver wakes up and sends a beacon, its active neighbor sends a beacon in its corresponding slot in the AF. It transmits DATA packet immediately after AF finishes.

Constructive interference will occur when multiple transmitters wait for a common receiver. Figure 3 demonstrates an example of constructive interference in CIRF. In the beginning, $S1$ and $S2$ are both waiting for R. After R wakes up and sends a beacon, the AF comes, in which $S1$ and $S2$ send beacon at their respective slot. Once AF finishes, $S1$ and $S2$ transmit DATA packet simultaneously. R receives the packet with higher probability due to constructive interference of the concurrent transmissions.

3) Determination of M: The AF length M is a critical parameter in the design of CIRF. On the one hand, the benefit from constructive interference is not obvious if M is too small. On the other hand, the gain from constructive interference is limited and too much overhead is introduced if M is too large.

Suppose there are K concurrent transmitters. Let A_i and τ_i denote the amplitude and phase offset of the ith transmitted signal. For simplicity, we assume the first signal is the original one and $\tau_1 = 0$. If delayed offset $\tau_i (1 < i \leq K)$ is less than $T_c = 0.5\mu s$, the original signal will be strengthened by the ith signal. According to [15], PRR can be derived from Eqs. (1) $\sim$ (4):

$$G = \sum_{i=1}^{K} (A_i cos \omega_c \tau_i)^2, \quad (1)$$

$$P_e = Q(\sqrt{2G\frac{S}{N}}), \tag{2}$$

$$P_s = \sum_{i=9}^{32} C(32,i)(1-P_e)^{32-i}P_e^i, \tag{3}$$

$$PRR = (1-P_s)^l. \tag{4}$$

Here G denotes the power gain of received signals; P_e denotes the bit error rate(BER); P_s denotes the symbol error rate(SER); $\omega_c = \pi/2T_c$ represents the radial frequency; $\frac{S}{N}$ represents the signal noise ratio of received signals; Q is the tail probability of the standard normal distribution; and l is the symbol number in a packet.

We calculate the relationship between PRR and the number of concurrent transmitters through simulations. The result is shown in Figure 5. The amplitude A_i is set to 1 for all signals, and the phase offset $\tau_i(1 < i \leq K)$ is randomly chosen from $[0, T_c]$. As expected, PRR can be significantly improved by leveraging constructive interference. However, as node number increases, the growth rate of PRR decreases. Especially when node number exceeds 6, the improvement of PRR is trivial. The reason may be that the maximum temporal displacement Δ of concurrent transmissions is closer to T_c when node number increases.

Let num denote the number of neighbors. For a node with more than 5 neighbors, M is set to 5 in CIRF and the top 5 neighbors with highest PRR are selected to complete AF. Otherwise, M just equals to num and all neighbors are selected in AF. To summarize, M is defined as follows:

$$M = \begin{cases} num & if(num \leq 5) \\ 5 & if(num > 5) \end{cases} \tag{5}$$

4) Memory Requirement: In CIRF, each node keeps a list of its neighbors. Information of neighbors is stored in a triplet(ID, M, k), representing neighbor's ID, neighbor's AF length and order of itself in the AF. This information is established in the neighbor discovery phase and will be kept constant for a long period. In the flooding progress, each node keeps the reception status of its neighbors, i.e., received or not, which can be represented by one bit. Overall, a node needs $O(D)$ memory space at most, where D is the maximum degree of a node in the network.

V. Evaluation

In this section, we evaluate the performance of CIRF through simulations. Specifically, we compare flooding delay, energy efficiency and delivery ratio of our design with other three solutions below.

- RI-MAC [13]: Each node unicasts DATA packet to each of its neighbors. During the flooding, collision is inevitable and backoff is used to deal with this case.
- ADB [10]: ADB is integrated with RI-MAC to exploit information at MAC layer. Extra footer appended to the DATA frame and ACKs is used to represent broadcast progress in ADB.
- Opportunistic Flooding [9]: Based on an energy optimal tree, opportunistic flooding makes a probabilistic forwarding decision at each sender to reduce the flooding delay and redundancy in transmission.

We generate 100 random network topologies for different node density settings, ranging from 50 to 300, and for different duty-cycle settings, ranging from 5% to 30%. In each network, the sink node originates 50 packets to flood to the whole network. We set time unit τ to 1s.

We use three performance metrics for evaluation. Flooding delay is defined as the time duration between when a packet was originated by the sink and when the packet reaches the last node. If the packet fails to reach all nodes in a network, the delay value is set to infinity. The number of active time slots, i.e., the total time a node has its radio on, is adopted to evaluate power efficiency. In order to evaluate reliability, we measure the percentage of nodes that have been reached by each flooding packet, indicated by delivery ratio.

We compare CIRF with ADB, opportunistic flooding and RI-MAC under different network settings in this section.

A. Different Node Densities

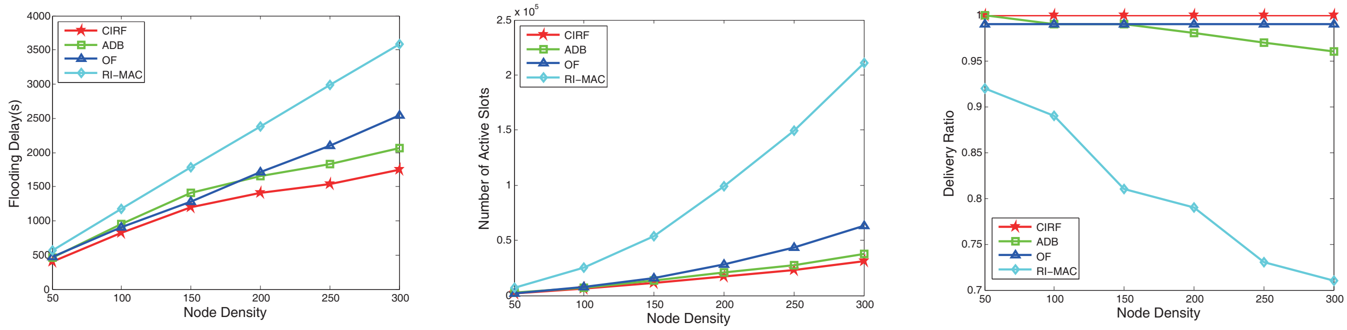
We present the simulation results in different network density settings in Figure 6. In Figure 6(a), the flooding delay increases as the node density increases, as expected. Compared with other schemes, CIRF reduces the flooding delay under different network density. And as node density increases from 50 to 300, the delay reduction increases. From Figure 6(b) we can see that, the number of active slots increases as node density increases, which is easy to understand. The number of active slots of CIRF is much lower than that of RI-MAC, and is less than that of ADB and opportunistic flooding under different node densities. Figure 6(c) shows delivery ratio of the four schemes. Better than opportunistic flooding, CIRF achieves 100% delivery flooding under different node densities, while the delivery ratio of ADB and RI-MAC decreases when network becomes dense.

B. Different Duty-Cycles

We also evaluate the performance of CIRF in networks with different duty-cycles. The results are shown in Figure 7. In Figure 7(a), we observe that the flooding delay decreases as network duty-cycle increases from 5% to 30%. Though not much, CIRF still outperforms ADB, opportunistic flooding and RI-MAC. We observe in Figure 7(b) that the number of active slots decreases as expected when duty-cycle increases. The number of active slots of CIRF is less than that of ADB and opportunistic flooding, and is much lower than that of RI-MAC under different duty-cycle settings. As shown in Figure 7(c), CIRF always achieves 100% delivery flooding, while the others can not realize reliable flooding.

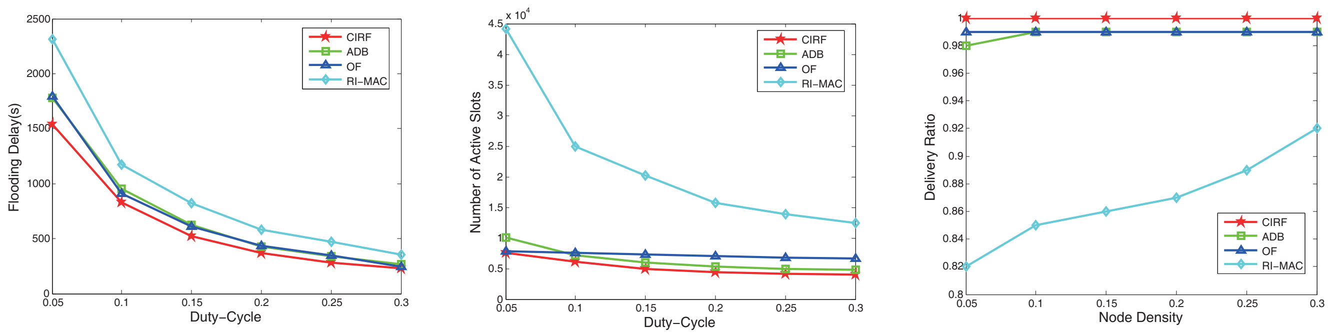
VI. Conclusion

In this work, we have presented the design and evaluation of Constructive Interference-based Reliable Flooding (CIRF) for reliable flooding in asynchronous duty-cycle WSNs with



(a) Flooding Delay (b) Number of Active Slots (c) Delivery Ratio

Fig. 6. Impact of node density.



(a) Flooding Delay (b) Number of Active Slots (c) Delivery Ratio

Fig. 7. Impact of duty cycle.

underlying RI-MAC. Constructive interference is employed and integrated with RI-MAC in CIRF to avoid redundant transmissions and improve PRR of the receiver, thus efficiently reduce the flooding latency and energy cost. Evaluation results show that CIRF achieves reliable flooding with reduced flooding latency and high energy efficiency and delivery ratio.

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