Idle-Slot Recycling in a Collision-Free Real-Time MAC Protocol

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***Abstract*—In wireless sensor networks (WSNs), timeliness is one of the most challenging problems for critical applications. Caccamo *et al.* designed a collision-free real-time MAC protocol for sensor networks by adopting the "cellular structure" in traditional telecommunication networks. They assumed that sensors are organized into many rigid hexagon cells and a router node is at the center of each cell to transmit inter-cell packets. By exploiting FDMA and TDMA, transmission collisions are avoided and real-time guarantees are provided.**

However, we observe that for inter-cell communication, idle-slots caused by the TDMA-based scheduling will degrade the throughput and delay performance of the entire network, especially for some real applications in which data flows have traffic-direction partiality characteristics. In the worst case, five sixths of inter-cell bandwidth will be wasted. In this paper, we propose four idle-slot recycling algorithms to improve channel utilization. Simulation results show that our proposed algorithms can greatly increase network throughput and decrease packet transmission delay, while the collision-free and real-time qualities of Caccamo's protocol are still retained.

I. Introduction

In recent years, wireless sensor networks (WSNs) have been identified as a promising technology for a wide variety of applications [1], such as environment monitoring and military surveillance, etc. Due to the tight interaction with physical environment, these applications are expected to have implicit/explicit real-time requirements [2].

One promising collision-free real-time MAC protocol is proposed by Caccamo et al. in [3]. The protocol adopts the "cellular structure" in traditional telecommunication networks [4], and it assumes a rigid deployment structure with a node (called router) at the center of each hexagon cell. Using FDMA (Frequency Division Multiple Access), different communication channels are assigned to neighboring cells; seven channels are needed for the whole network. Since each cell is assigned a channel that is different from its six adjacent cells, all cells can transmit simultaneously without conflicts. Time is also divided into periodical intra-cell slots and inter-cell slots. During an intra-cell slot, sensors inside each cell use the same local channel to transmit packets. Traffic across

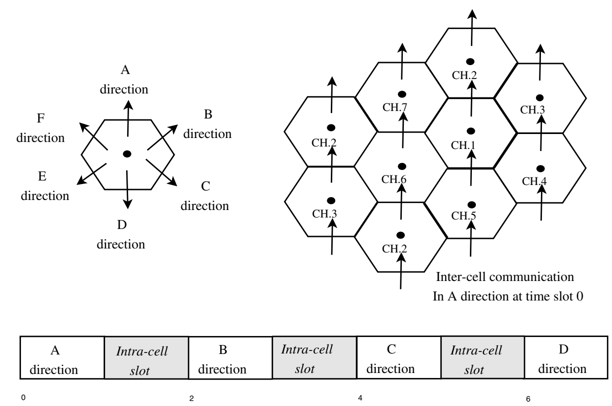

Fig. 1. Collision-Free Real-Time MAC Protocol[3]

cells is relayed by the routers at the center of each cell. A router is a more capable node equipped with both a transmitter and a receiver, such that it can send a packet (in the local channel) and receive a packet (in a neighbor's channel) simultaneously. The inter-cell communication of the whole network is synchronized by a TDMA (Time Division Multiple Access) scheduling policy, in which all routers simultaneously transmit in the same direction for each inter-cell time slot. There are six directions (A-F), and they are chosen one by one in consecutive inter-cell time slots. For example, as illustrated in Fig. 1, at time slot 0, all routers transmit in direction A. Under this protocol, it is guaranteed that no collision will occur in intra-cell and inter-cell communication, and a hard bound for packet forwarding time can be given.

However, we may observe that the inter-cell slots are equally and periodically assigned to the six directions, while for many applications, it is very likely that during a certain period of time, the local traffic only goes along a few directions. We call this characteristic as *traffic-direction partiality*. It is easy to see that for data flows with traffic-direction partiality, a lot of inter-cell slots will be idle. In the worst case, five sixths of inter-cell bandwidth will be wasted.

Previously, there are two types of TDMA idle slots reuse. The first type is on spacial time reuse, which tries to assign the same time slot to maximal number of geographically separated nodes so that interference is minimized and system

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throughput is improved [5], [6], [7]. The other type, which is similar to the problem that we are solving here, is focused on reusing idle time slots that are caused by unbacklogged flows [8], [9], [10]. However the existing solutions are designed for some specific TDMA systems and cannot be directly applied to the cellular structured networks studied in this paper .

In this paper, we propose four algorithms (R-ISR, MRU-ISR, I-ISR, ID-ISR) to reuse the inter-cell idle-slots. When a time slot becomes idle, the four algorithms employ different strategies to select a direction to send (receive) a packet, by which the idle-slot is expected to be reused. In R-ISR, as the simplest way, the direction is randomly selected. In MRU-ISR, historical transmission information is exploited, and the direction of the most recent successful transmission is picked. By piggybacking buffer status in packets, I-ISR and ID-ISR make use of future traffic information of neighboring routers to better choose the recycling direction. Our proposed algorithms are able to greatly improve network throughput and reduce packet transmission delay. ID-ISR can also allocate the extra bandwidth (gained by idle-slot recycling) among flows fairly. For all the algorithms, the collision-free and real-time qualities of the original protocol are still retained. We evaluate the proposed algorithms through simulations.

The rest of the paper is organized as follows: The problem is defined in Section II. In Section III, four opportunistic idle-slot recycling algorithms are presented and compared in details. In Section IV, the effectiveness of the proposed algorithms is evaluated through simulations. Finally, we conclude the paper in Section V.

II. Problem Definition

As we have mentioned, in a cellular structured sensor network with the original protocol given in [3], a considerable amount of inter-cell time slots can be idle and a large portion of bandwidth is wasted. We try to solve this problem by designing algorithms to properly reuse the idle-slots during inter-cell communication. In this section we take a closer observation on the occurrences of idle-slots and the feasibility of idle-slot reuse. We also introduce the major concerns that must be addressed when designing idle-slot reuse algorithms. To simplify description, in the following sections of this paper, if not explicitly specified, the terms *time slot* and *idle-slot* always denote inter-cell time slot and inter-cell idle-slot.

The traffic-direction partiality characteristic is very common for sensor networks, where most data packets are forwarded from data sources to one or several BSs (base stations). The occurrence of idle-slots is a direct result of this traffic-direction partiality characteristic. For example, suppose that a BS is located to the direction A of a router R, most traffic relayed by R would be heading to direction A. Thus during the time slots that are assigned to the other five directions, R will not receive nor send any packets. This is obviously a waste of channel capacity, as during these idle-slots R and its neighboring routers indeed can keep sending and receiving packets along direction A.

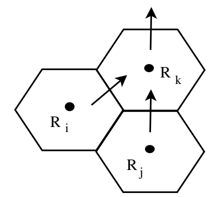

Fig. 2. Fairness in Idle-Slot Recycling

There are two types of idle-slots for a router. If during a time slot a router R does not have any packets to send to the pre-assigned direction x, we call it as a *sending idle-slot* of R. Similarly, if during a time slot there is no any packets from pre-assigned direction x to R, we call it as a *receiving idle-slot* of R. For two neighboring routers to reuse an idle-slot, the sending idle-slot of the sender and the receiving idle-slot of the receiver must be matched together, by which we mean that the sender must choose to use the idle-slot to transmit packets to the receiver, and the receiver must also choose to use the idle-slot to receive packets from the sender. It is worth noting that due to the cellular structure and the seven distinct channels, idle-slot reuse will not cause transmission collisions. For example, as displayed in Fig. 2, even R_i mistakenly reuses its sending idle-slot to send a packet to R_k in direction A, the transmission between R_k and R_j will not be interrupted because R_k and R_j use the same channel while R_i uses a different one.

To effectively and decently reuse idle-slots, we need to answer the following three questions:

(1) Do routers need to exchange idle-slot information?

(2) How do routers maximize the probability of successful idle-slot reuse?

(3) How do routers reuse these idle-slots fairly?

For question (1), it depends on how effectively we want to reuse the idle-slots. By exchanging idle-slot information among neighboring routers, it is expected that better performance can be achieved. We can piggyback idle-slot information in data and ACK packets, and as the attached information can be as short as several bits, the introduced overhead is acceptable.

For question (2), the most challenging problem for idle-slot reuse is that, when two routers have sending and receiving idle-slot respectively, how they can have a high probability to pick each other to reuse this idle-slot. Because they both have five other neighbors, the probability of successful reuse can be as low as 4%, if they just flip a coin.

For question (3), fairness is another concern, which is important for a network to provide better service. As shown in Fig. 2, if router R_i and R_j both have many data packets to send to R_k, R_k should try to fairly allocate its receiving idle-slots between them.

We will further discuss these questions and give our solutions in the next section.

III. IDLE-SLOT RECYCLING

In this Section, four idle-slot recycling algorithms will be proposed and compared. The basic idea is that, some idle-slot reuse agreements will be set up between routers to increase the probability of successful idle-slot reuse. The fairness issue will also be addressed.

A. Random Idle-Slot Recycling (R-ISR)

R-ISR is a very simple way to reuse idle-slots: at an arbitrary time slot, if a router R_j has a sending idle-slot (receiving idle-slot), it randomly picks up one direction among other five directions to send (receive) a packet.

The problem of this algorithm is also straightforward: the probability of successful idle-slot reuse can be very small. Suppose during the same time slot two neighboring routers R_j and R_k have one sending idle-slot and one receiving idle-slot respectively, because both R_j and R_k have five other neighbors, the probability for them to pick up each other to reuse their idle-slots is as low as 4%.

B. Most Recently Used Idle-Slot Recycling (MRU-ISR)

In a typical multi-hop wireless sensor network, a data source periodically reports collected data to BSs. So once a router node R_i successfully receives a packet from its neighbor R_j, R_i may anticipate that there will be more following packets from R_j.

Based on this observation, we designed the MRU-ISR, a quite simple yet efficient idle-slot recycling algorithm. The basic idea is that once router R_j successfully transmits a packet to its neighbor R_i, an *opportunistic preemptive idle-slot reuse agreement* (OP-agreement) is immediately set up between R_i and R_j, and then if R_j has more sending idle-slots, it will try to send packets to R_i and also R_i will try to receive packets from R_j at its receiving idle-slots.

We call this idle-slot reuse agreement *opportunistic* and *preemptive* because these agreements between routers are only based on the current transmission and a "guess" for future traffic. Besides, these agreements might be set up and preempted frequently and dynamically according to the most recent successful packet transmissions. For example, as shown in Fig. 3, in direction A, the router R_j transmits a packet to R_k and then an OP-agreement is established between them. In the next direction B, if R_k receives a packet from its another neighbor R_i, a new OP-agreement is immediately set up between R_k and R_i without regard to the previous OP-agreement between R_k and R_j. So in the following direction C, if R_k has a receiving idle-slot, it will try to reuse this idle-slot with R_i instead of R_j.

Due to the traffic-direction partiality nature of data flows, MRU-ISR works much better than R-ISR. However, since OP-agreement is set up opportunistically without accurate information for future traffic, it may not always work well. As shown in Fig. 3, when R_k releases its OP-agreement with R_j and establishes a new one with R_i, it actually does not know whether R_i has more packets for it or not in the near future. If R_i has no more packets or has no sending idle-slot in the next direction C, then the receiving idle-slot of R_k will be wasted and at the same time the sending idle-slot of R_j can not be utilized. Another problem is fairness, since the OP-agreement is preemptive, some nodes might have more chances to reuse idle-slots than others. For example, as illustrated in Fig. 3, suppose direction A is followed by direction B, if both R_i and R_j have many packets to send to R_k, R_i will always be able to preempt the OP-agreement from R_j, such that R_i may send more packets than R_j. Therefore, we will propose another two algorithms to further enhance the performance of MRU-ISR in the following subsections.

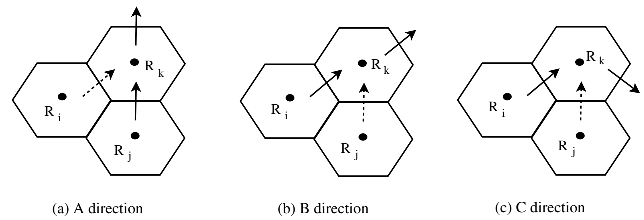

Fig. 3. Opportunistic Preemptive Idle-slot Reuse Agreement

C. Informed Idle-Slot Recycling (I-ISR)

The main differences between MRU-ISR and I-ISR are that idle-slot reuse agreement is set up according to more accurate future traffic information and each agreement will be kept for a certain amount of time and cannot be arbitrarily preempted. I-ISR is outlined as follows:

(1) Each idle-slot reuse agreement has a *reuse point* (RP). If RP is greater than 0, the agreement is called an *informed coordinated idle-slot reuse agreement* (IC-agreement) and it cannot be preempted by others. On the other hand, if RP is less than 1, the agreement is called an *informed preemptive idle-slot reuse agreement* (IP-agreement), which means new agreement can be set up to replace it.

(2) When a router R_i sends a data packet to R_j, if R_i has more packets for R_j and R_i does not have any existing IC-agreement with others, R_i will attach its buffer status and an *idle-slot reuse request* (I-Request) in the data packet.

(3) Once R_j receives an I-Request from R_i, if R_j has receiving idle-slots and R_j has no existing IP-agreement with R_i nor IC-agreement with others, R_j sets up an IC-agreement with R_i (RP is initialized to a positive number, e.g. 10 in our simulations). The agreement set up confirmation will be attached in the ACK packet to R_i.

(4) Suppose there is an IC-agreement (IP-agreement) between R_i and R_j. When R_i has a sending idle-slot, R_i will try to send a packet to R_j. On the other hand, R_j will also try to receive a packet from R_i at its receiving idle-slots. If they succeed to reuse an idle-slot, the RP of the IC-agreement (IP-agreement) is deducted by a small number (e.g. 1), otherwise RP is deducted by a larger number (e.g. 3). When RP of an

IC-agreement is decreased to less than 1, the IC-agreement is converted to an IP-agreement.

Since the future traffic information is exploited, the problem caused by the opportunism in MRU-ISR is relieved. Moreover, the idle-slot reuse chances are shared among neighbors more fairly by introducing two types of agreements. For example, as shown in Fig. 3, we pointed out that in MRU-ISR, R_i will always preempt the OP-agreement from R_j. But in I-ISR, the IC-agreement between R_j and R_k cannot be preempted by R_i before it turns to an IP-agreement.

D. Informed Directional Idle-Slot Recycling (ID-ISR)

For the above algorithms, if two routers set up an agreement, it will be applied to all their six directions and the directional reuse is not taken into account. For example, as shown in Fig. 4, suppose that R_i has packets for both R_k and R_j, and R_i has an idle-slot reuse agreement with R_k. In direction E, R_i can reuse its sending idle-slot with R_k, while in direction A, R_i cannot successfully transmit to R_k because R_j has packets for R_k. As we can see, in fact, in direction A, R_i should reuse with R_j since R_j has no any packet to receive. So, if the idle-slot reuse agreements can be set up by directions, we can expect to reuse more idle-slots.

Thus, based on I-ISR, ID-ISR is proposed to reuse idle-slots by directions. The ID-ISR is outlined as follows:

(1) As in I-ISR, there are two types of idle-slot reuse agreements, IP-agreement and IC-agreement, and each agreement has a RP. For each router R_i, it has six sending directions and six receiving directions. At the beginning, all these sending and receiving directions are marked as unreserved. An agreement can be set up between one sending direction and one receiving direction of two routers.

(2) When R_i sends a data packet to R_j, if R_i has more packets for R_j and R_i has some unreserved sending directions, R_i will attach its buffer status, unreserved sending directions and an I-Request in the data packet.

(3) Once R_j receives an I-Request from R_i, if R_j has unreserved receiving directions, R_j sets up IC-agreements with R_i in matched directions (i.e. in these directions, R_j and R_i have unreserved receiving and sending directions respectively). Then, R_j marks the corresponding receiving directions as reserved. But if R_j already has an existing IP-agreement with R_i in a certain direction, R_j just keeps the IP-agreement. The agreement set up confirmation will be sent back to R_i via ACK. Upon receiving the ACK, R_i sets up agreements and marks its sending directions accordingly.

(4) Suppose R_i and R_j have an IC-agreement (IP-agreement) in direction A. When R_i has a sending idle-slot in direction A, R_i will try to send a packet to R_j. On the other hand, when R_j has a receiving idle-slot in direction A, R_j will try to receive a packet from R_i. If they succeed to reuse an idle-slot, the RP of the IC-agreement (IP-agreement) is deduced by a small number, otherwise RP is decreased by a larger number. When the RP of an IC-agreement is less than 1, the IC-agreement is converted to an IP-agreement and the corresponding direction is marked as unreserved.

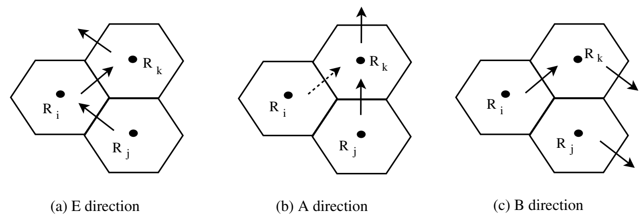

Fig. 4. Informed Directional Idle-Slot Recycling

IV. SIMULATION

We evaluate our proposed idle-slot recycling algorithms (R-ISR, MRU-ISR, I-ISR, and ID-ISR) through two sets of simulations. We first study their throughput and delay performance, and then we focus on the flow rate fairness they attained. In our simulations, there are 200 router nodes (cells) deployed in a squared area. Each inter-cell and intra-cell time slot is 0.01 second. Only inter-cell communications are simulated and during each inter-cell time slot one packet can be transmitted. Every packet has a fixed length of 512 bytes. Simulation results show that all the three algorithms (MRU-ISR, I-ISR, and ID-ISR) can greatly improve network throughput and decrease packet transmission delay, where ID-ISR gives the highest throughput. In addition, ID-ISR can achieve better fairness than MRU-ISR and I-ISR. In this section, the original protocol in [3] is used as a baseline for comparison purpose, and it is referred as *no recycling*.

In the first set of simulations, there are two BSs (base stations), one of which is located at the northwest corner of the network and the other one is located at the northeast corner. 10 out of the 200 nodes are randomly selected as data sources and they periodically send packets to one of the two BSs. We run the simulation for 200 seconds. Fig. 5 compares the network throughput achieved by different algorithms when varying the sending rate of each data source. We can see that with the sending rate increasing the network quickly gets congested if no idle-slot reuse is exploited. In other words, the network bandwidth is not well utilized. R-ISR achieves higher throughput but the improvement is limited. As we expected, the other three algorithms (MRU-ISR, I-ISR, and ID-ISR) are able to improve the network throughput dramatically. Among the three algorithms, ID-ISR gets the best performance and I-ISR is also better than MRU-ISR, because informed algorithms can obtain more accurate information about future traffic, by which they can better reuse idle-slots accordingly.

We study the delay performance of the algorithms when the network traffic is light, as packets will be dropped when congestion happens. Fig. 6 shows the simulation results. Because idle-slots are well utilized, the packet transmission delays of MRU-ISR, I-ISR and ID-ISR are much smaller than

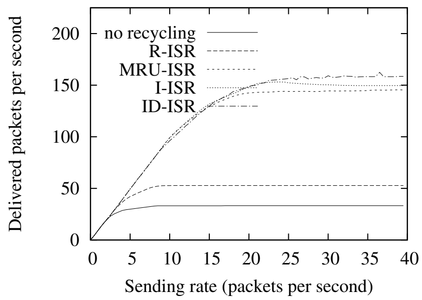

Fig. 5. Network throughput with different source sending rates

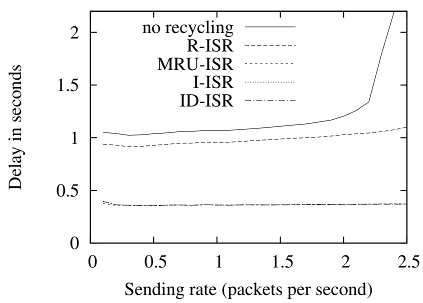

Fig. 6. Transmission delay with different source sending rates

those of the other two algorithms. The three curves (MRU-ISR, I-ISR, and ID-ISR) stick together because they all work very well and approach the optimal delay performance.

In the next set of simulations, we evaluate the fairness property. We set up two data flows, one of which goes from north to south and the other one goes from west to east, and they cross each other at the center of the network, where the crossing node becomes the bottleneck. The sending rates of the two flows are set to high enough, such that they are always backlogged at the bottleneck. We observe the effective throughput of the two flows when they are competing with each other. From Table I, no recycling and R-ISR achieve near perfect fairness because they only allocate the same minimum bandwidth to each of the two flows and leave the rest bandwidth (idle-slots) unused, or very limitedly reused. As the other three algorithms (MRU-ISR, I-ISR, and ID-ISR) exploit idle-slots, the throughput is improved. Especially, ID-ISR achieves the best fairness because the idle-slot recycling in ID-ISR is more elegantly coordinated.

TABLE I
THROUGHPUT (PACKETS PER SECOND) FAIRNESS FOR TWO CROSSING FLOWS

	flow 1	**flow 2**
no recycling	8.28	8.29
R-ISR	8.95	9.06
MRU-ISR	16.59	33.29
I-ISR	29.03	20.85
ID-ISR	23.40	26.09

V. CONCLUSION

The MAC protocol proposed in [3] for cellular structured sensor networks gives a promising solution for applications with real-time requirements. By eliminating transmission collisions, it saves energy and can potentially increase network throughput. However, when traffic-direction partiality exists, which is very common in sensor networks, a lot of time slots become idle and the network capacity is not fully utilized.

In this paper, we proposed four idle-slot recycling algorithms (R-ISR, MRU-ISR, I-ISR, ID-ISR) that can greatly improve network throughput and reduce packet transmission delay. Among the four algorithms, R-ISR and MRU-ISR do not need any auxiliary information, and MRU-ISR already performs quite well for most application scenarios. By making use of the traffic information of neighboring cells, I-ISR and ID-ISR improve the network performance further. ID-ISR achieves the best throughput, while it is able to allocate bandwidth among data flows fairly. Moreover, for all the four algorithms, the collision-free and real-time qualities of the original protocol are retained. The performance of the algorithms is evaluated through simulations.

Our future work will be focused on extending the algorithms to more general TDMA schemes without cellular structures.

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