Priority-Based Delay Mitigation for Event-Monitoring IEEE 802.15.4 LR-WPANs

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Abstract—IEEE 802.15.4 slotted carrier-sense multiple access with collision avoidance (CSMA-CA) adopts periodic sleeping for energy efficiency support. However, such a periodic sleeping mechanism, especially with contention-based medium access, tends to cause additional sleep delay due to heavy contention. In this letter, we propose a priority-based scheme, comprising Frame Tailoring and Priority Toning, in order to relax such a problematic delay and guarantee time-bounded delivery of high priority packets in event-monitoring networks.

Index Terms—IEEE 802.15.4, priority-based, sleep delay, event-monitoring.

I. INTRODUCTION

IEEE 802.15.4 for Low-Rate Wireless Personal Area Networks (LR-WPANs) [1] was standardized in 2003. This specification, which defines both physical (PHY) and medium access control (MAC) layers for low-rate wireless networks, can be used for diverse emerging applications featured by long lifetime and low-rate wireless communication. In this letter, we focus on inherent long packet delay of IEEE 802.15.4 slotted CSMA-CA, which has common characteristics with wireless sensor MAC protocols, in the context of event-monitoring networks. Since the unslotted CSMA-CA in IEEE 802.15.4 for nonbeacon-enabled mode has no power saving mechanism, the slotted version for beacon-enabled mode, in which coordinated periodic sleeping is adopted, is considered here for enhancement.

In the literature on wireless sensor networks, Wei Ye et al. improve their original SMAC scheme with the coordinated adaptive sleeping method to lessen delay [2]. In [3], the authors identify the Data Forward Interruption (DFI), which is also referred to as sleep delay in [2], in existing wireless sensor MAC protocols including SMAC [2] and TMAC [4], and they propose DMAC to alleviate the influence of the DFI. In this context, sleep delay refers to a portion of packet delay caused by sleep periods originally designed for energy saving. Gang Lu et al. analyze this type of delay under general assumptions in order to find the optimal sleep schedule for two specific topologies in [5].

Even though sleep delay is relaxed by such an algorithm as DMAC proposed in [3], once a contention-based medium access is considered, a packet transmission might experience even more unnecessary sleep periods when a node fails to grab the medium due to contention, especially, around the sink node since all network traffic converges to it. That is, a packet relaying can be easily delayed by several sleep periods due to heavy contention on the way to the sink node although total traffic in a network remains relatively low. The existing MAC protocols, however, often assume very low traffic load across the entire network so that the impact of this type of sleep delay, referred to as contention-inherited sleep delay, has not been considered.

To mitigate the contention-inherited sleep delay, we propose a priority-based scheme comprising Frame Tailoring (FRT) and Priority Toning (PRT). The proposed scheme exploits the packet priority to temporally separate the medium access by different groups of nodes according to the corresponding packets’ priority. This virtually encourages each node to access the medium as if their medium access would be scheduled via “pseudo” time division multiple access (TDMA). As a result, every group of nodes ends up experiencing less contention compared to the situation without prioritization, thus reducing the probability of contention-inherited sleep delay occurrence. Moreover, by following the strict priority-based ordering, a high priority packet can be provided bounded delay so that a packet containing the notification of certain event detection can be delivered to the sink node within acceptable delay.

II. PROPOSED PRIORITY-BASED SCHEME

In this letter, we assume that there are two types of priority, i.e., high and normal priority, which can be assigned either by MAC protocol itself or by upper layer protocols. We also assume that the normal-priority packets are transmitted via the standard CSMA-CA scheme as defined in the standard.

The purpose of the proposed scheme is to reduce the probability of contention-inherited sleep delay occurrence via powerful prioritization to temporally separate the medium access by different groups of nodes, while guaranteeing reasonably bounded delay of high-priority packets. For this, one can easily find that there are two medium access parameters useful to differentiate packet transmissions in slotted CSMA-CA of IEEE 802.15.4: (1) the number of CCAs, determining whether the medium is busy or idle, performed prior to each packet transmission and (2) the range of backoff counter, determined by backoff exponent BE.1

First, the standard specifies that a transmitter node performs the CCA twice in order to protect acknowledgment (ACK) packets. Each CCA occurs at the boundary of a backoff slot, composed of 20 physical-layer symbols, and eight out of these

1Similar approaches have been employed in IEEE 802.11e MAC for WLANs [6], but having a different CSMA-CA version, the approaches for IEEE 802.15.4 become quite different as shown later.
20 symbols in a backoff slot are measured for each CCA. When an ACK packet is expected, the receiver shall send it after $t_{ACK}$ time which varies from 12 to 31 symbols, as will be detailed below. Therefore, one-time CCA by a transmitter node can potentially cause a collision between a newly-transmitted packet and an ACK packet. That is, there is no standard-compliant way to enable faster transmission (compared to the standard CSMA-CA) by adjusting the number of CCAs. Nevertheless, it is obvious that one-time CCA can offer a very powerful prioritization. Secondly, for a backoff counter, the range of the counter drawn for a high-priority packet’s backoff procedure should be a constant or should be bounded by a constant value smaller than a normal packet’s in order to transmit high-priority packets faster than normal ones.

**Frame Tailoring (FRT)** strategy is proposed to avoid ACK and data packet collision while allowing one-time CCA so that it can be exploited to provide strong prioritization in addition to the standard CSMA-CA. Moreover, this strategy helps improve the performance of a network by reducing CCA overheads by half. Depending on packet length, the length of $t_{ACK}$ is determined as depicted in Fig. 1. Let us define the term frame tail as the length of the remainder after the total packet length is divided by the backoff slot length (i.e., 20 symbols). If a frame tail is from 0 to 8 symbols, a receiver transmits an ACK packet at the very next backoff slot boundary as depicted in Fig. 1 (a) and (b). On the other hand, if a frame tail ranges from 9 to 19 symbols, an ACK transmission by the receiver is postponed to one backoff slot after the next backoff slot boundary to allow adequate time to prepare the ACK transmission. As a result, $t_{ACK}$ becomes more than 20 symbols as shown in Fig. 1 (c). Then, the CCA operations of other containing nodes during this time interval report that the medium is idle. To protect ACK transmissions in such cases, two-time CCAs are mandated in IEEE 802.15.4 slotted CSMA-CA.

FRT strategy is to adjust each data packet length so that $t_{ACK}$ becomes exactly 12 symbols as shown in Fig. 1 (b). By doing so, one-time CCA will never declare an idle medium during the time period between a data and an ACK, and hence by adopting one-time CCA for a particular transmission, high prioritization can be achieved. A transmitter node first determines whether the tailoring is needed or not. Once a node decides that it is required, it pads zeros at the end of its packet as many as needed.\(^2\) However, the length field of a physical layer protocol data unit (PPDU) conserves the original length of the packet. This is for a receiver node to receive the packet correctly while the attached part of the packet merely plays the role that other nodes except for the targeted receiver assess the medium as in busy status.

In addition to Frame Tailoring, we propose **Priority Toning** (PRT) strategy which is aimed to allocate some portion of active period to the transmission of high-priority packets. With PRT, a tone signal is transmitted by child nodes, which have a high-priority packet, in the backoff slot immediately before a periodic beacon transmission. The coordinator node, which transmits beacons, has to wake up one backoff slot earlier and listen to the medium to determine whether a tone signal is transmitted by its child nodes or not. If it detects a tone signal, which might be from multiple nodes, the notification of a high-priority packet existence is conveyed in the subsequent beacon packet so that the beacon makes all other nodes without a high-priority packet defer their transmissions by a pre-specified amount of time in order not to contend with the nodes with a high-priority packet. Note that the initial part of an active period is inclined to be competitive in contention because every node received packets from the upper layer during the sleep period tries to send them at this moment, and PRT is likely to reduce the competition in this interval by temporally separating the contentions for high and normal priority packets.

### III. Simulation Results

We perform a simulation with a star-topology network in order to evaluate our proposed scheme using the ns-2 simulator. A star topology emulates one-hop network or the most competitive part of a multihop network, i.e., the sink node and its one-hop neighbors\(^3\). All nodes except the coordinator generate Constant Bit Rate (CBR) traffic with a payload of which the length follows the uniform distribution ranging from 20 to 96 bytes to evaluate the performance of Frame Tailoring (FRT). For Priority Toning (PRT), eight backoff slot deferment is chosen. The duty cycle and the length of one period, comprising an active and sleep period, are set to 6.25% and 492ms, respectively, to imitate a time-critical event-monitoring network, and $BE$ is limited to 3 for high-priority packets that occupy 10% of the entire traffic.

In Fig. 2, the probability of transmission deferment by competitive contention of each strategy combination is depicted in order to confirm the reduction of the contention-inherited sleep delay. FRT+ and PRT+ represent the adoption of the FRT and PRT strategy, respectively, while a ‘−’ sign instead of ‘+’ implies that the strategy is not adopted. For example, ‘High, FRT+’, PRT+’ indicates the high-priority packets’ probability of the proposed priority-based scheme, i.e., with both FRT and PRT. High-priority packets transmitted by the proposed scheme basically never experience such a deferment until the

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\(^2\)This function requires hardware support, and it might not be available in some of today’s chipsets, e.g., CC2420 [7].

\(^3\)For multihop simulation, an additional algorithm to schedule each coordinator’s active period is required upon 802.15.4 MAC layer. To focus on the sole performance of the proposed scheme, we limit the scope of the simulations.
traffic load reaches 4.5 kb/s. It is notable that even normal-priority packets maintain a little lower probability than that of a packet transmitted by the standard method. In this figure, the impact of FRT seems modest until the traffic load reaches 4.5 kb/s. It is, however, found that FRT prioritizes transmissions more significantly than PRT when the network load exceeds 4.5 kb/s. That is, a reversal is observed at 5 kb/s between the probability of ‘High, FRT-, PRT+’ and that of ‘High, FRT+, PRT-’. Therefore, FRT deserves to be adopted in order to temper the cause of high-priority packet’s contention-inherited sleep delay under heavy traffic load, while PRT serves to considerably separate medium access in accordance with packet priority under low traffic load. It should be also noted that, if a network is composed of multi-hops, the amount of end-to-end relaxation will be even more significant.

Fig. 3 presents one-hop packet delays as the traffic load applied to the network increases. Both high and normal-priority packets of the proposed scheme experience less delay than those of the standard CSMA-CA. At the same time, the delay of high-priority packets is bounded by 1.3 seconds even when the applied traffic load is over 6 kb/s, which implies the guarantee of reliable delivery of important packets under heavy traffic load. Note that the point of an abrupt increase in the standard CSMA-CA’s delay at 4 kb/s is shifted to the point of 4.5 kb/s by the proposed scheme, implying the network capacity increase. Moreover, we can imagine that if the sleep period of a network becomes longer, the amount of delay mitigation would be magnified.

Applied the radio characteristic in [7], we also measure the energy consumption caused by the standard CSMA-CA and our scheme. The standard CSMA-CA without any modification consumes 122.4 mJ for 100 seconds while the proposed scheme consumes 114.7 mJ. Apparently, this temperate energy deduction mainly comes from the reduction of RF radio’s receiving time.

IV. CONCLUSION

We have introduced the priority-based scheme to mitigate long delay in event-monitoring 802.15.4 networks. By adopting the proposed Frame Tailoring and Priority Toning strategies, the probability of transmission deferment to the next active period due to competitive contention is relaxed, and bounded delay is provided to high-priority packets. These benefit from the fact that the proposed scheme effectively separates the medium access of each group of packet transmissions according to packet’s priority.

REFERENCES