Slotted Contention-Based Energy-Efficient MAC Protocols in Delay-Sensitive Wireless Sensor Networks

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***Abstract*—This paper considers slotted duty-cycled medium access control (MAC) protocols, where sensor nodes periodically and synchronously alternate their operations between active and sleep modes to save energy. Communications can occur only when nodes are in active mode. The synchronous feature makes these protocols more appropriate for delay-sensitive applications than asynchronous protocols. With asynchronous protocols, additional delay is needed for the sender to meet the receiver's active period. This is eliminated with synchronous approaches, where nodes sleep and wake up all together. Moreover, the contention-based feature makes the protocols –considered in this paper– conceptually distributed and more dynamic compared to TDMA protocols. Duty cycling allows obtaining significant energy saving vs. full duty cycle (sleepless) protocols. However, it may result in significant latency. Forwarding a packet over multiple hops often requires multiple operational cycles (sleep latency), i.e. nodes have to wait for the next cycle to forward data at each hop. Timeliness issues of slotted contention-based MAC protocols are dealt with in this paper, where a comprehensive review and taxonomy is provided. The main contribution is to study and classify the protocols from the delay-efficiency perspective.**

***Index Terms*—WSN; MAC; Synchronous Protocols; Delay.**

I. Introduction

While earlier research works on WSNs have mainly focused on monitoring applications that are based on low-rate data collection [1], current WSN applications become more complex. They range from health, to industrial monitoring, transportation, and automation [2]. In addition to energy constraint that was almost the only metric for consideration in earlier applications, new constraints appear with the emerging applications, such latency, security and reliability. Given that the radio interface is likely to consume the largest amount of a node's battery; power saving is the main purpose of the MAC protocol that manages the access to the shared communication medium. Energy conservation is achieved at the MAC layer through duty-cycling of the radio. This consists of repeatedly turning on/off the radio and, and of attempting keeping the radio off as long as possible. A node needs to be aware of its neighbors' sleep/active schedules, since messages cannot be exchanged unless both the transmitter and the receiver are awake. In synchronous schemes, this issue is tackled by having all neighboring nodes synchronized on one common schedule. Synchronous schemes are supposed to obtain significant energy saving compared to full-duty-cycle contention-based protocols. Moreover, synchronous MAC ensure quick sender-to-receiver forwarding compared to asynchronous MAC, where the sender has to wait for the receiver to wake up. Further, contention-based protocols are more appropriate to dynamic WSN compared to TDMA-based, where the transmission schedule must be established by some central node or agreed amongst nodes. Making the schedule adaptable to nodes traffic (to avoid unused slots) is challenging with TDMA, contrary to the contention approach that is naturally distributed and adapts to traffic loads. However, forwarding a packet over multiple hops often requires multiple operational cycles, where at each hop, the relay node has to wait for the next cycle before forwarding data. This is known as sleep delay. Formally speaking, the end-to-end delay, ETE_Delay, is expressed as:

$$ETE\_Delay = \sum_{i}^{k} Delay_i, \qquad (1)$$

where $Delay_i$ is the delay at hop i. Ensuring low-latency in WSN is challenging due to sensor nodes' limitations in energy supply, limited bandwidth, unstable wireless links, etc. This paper deals with MAC timeliness issues and provides a comprehensive review and taxonomy of the literature. More focus will be given to the forwarding delay experienced by the protocols. The remainder of this paper is organized as follows. Sec. II presents the related work, while Sec. III presents static schedules that are distinguished from all the other adaptive ones. Sec. IV presents grouped schedules, repeated schedules, staggered schedules, and last but not the, least reservation schedules. All the reviewed protocols are summarized in Sec. V, together with some discussions and new directions. Finally, Sec. VI draws the conclusions.

II. Related Work

Existing contention-based MAC protocols for WSN can be split down into two categories, synchronous vs. asynchronous protocols. The latter have no communication overhead, contrary to the former. Nonetheless, communicating nodes are totally decoupled in asynchronous protocols. This may significantly increase the delay for the sender to meet the receiver's active period. Contrary to TDMA-based protocols, synchronous and asynchronous contention-based protocols may cause significant delay, as the nodes may require multiple contentions before acquiring the channel. Moreover, the possibility of collision is much higher due to grouping communications into small active parts of the slots. Apart from this, slotted protocols mainly differ from each other

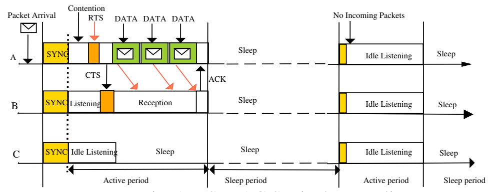

Fig. 1.a S-MAC Static duty-cycling.

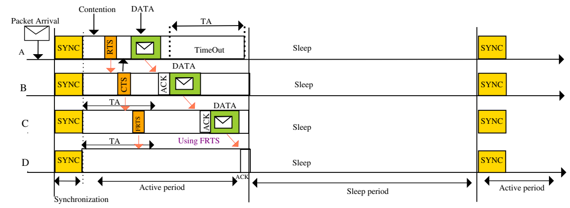

Fig. 1.b T-MAC's FRTS mechanism to cope with early sleep problem.

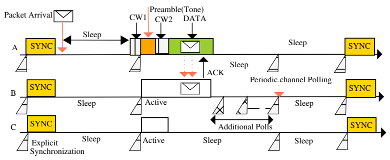

Fig. 1.c SCP-MAC's repeated wake-up periods.

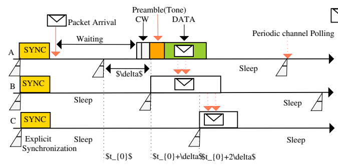

Fig. 1.d LEMR's Staggered channel polling.

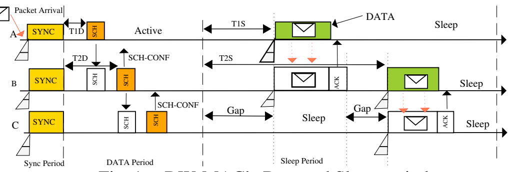

Fig. 1.e DW-MAC's Data and Sleep periods.

in their policies that determine when to switch active/sleep modes. [3] and [4] present reviews WSN's MAC protocols, where protocols are evaluated from the energy efficiency perspectives. [5] proposes a different taxonomy, in which the protocols are classified according to the problem they target. In [6], latency of some energy-efficient MAC protocols for low-data rate applications has been analyzed, but without a comprehensive review or classification. The work of [7] focuses on two essential network performances; delay and reliability, which are essential in mission-critical data delivery. The authors accordingly classify MAC protocols into protocols that provide delay decrease (contention-based), and those that ensure delay guarantee (contention-free). Much more interest has been given to contention-free protocols, which provide deterministic delay/reliability guarantee. Nevertheless, such protocols, such as TDMA, are complex and sensitive to link instability or frequent topology change, which makes it are hard for implementation in real motes. The main contribution of this paper is to introduce a novel taxonomy on the basis of the mechanisms that affect the delay, and to provide a review on *synchronous contention-based* MAC protocols. The proposed taxonomy is more focused; it is limited to delay-sensitivity. Based on the duty-cycling policy and its impact on the delay, existing synchronized slotted MAC protocols are divided into static and dynamic duty-cycling. The latter can be split up into four categories: grouped, repeated, staggered, and reservation schedules.

III. Static Duty-cycling Protocols

In static duty-cycling scheme, nodes follow a common a priori fixed schedule, which is completely decoupled with the network traffic load fluctuation. S-MAC [8] is a typical protocol that uses static schedule. It is considered as a canonical MAC protocol, and it is used in this paper as a baseline reference for protocol comparison. In S-MAC, schedules are exchanged at the beginning of a slot via *SYNC* packets, which forms several virtual clusters. This results in simultaneous self-schedule selection and large end-to-end delays (ETE). Therefore, the wake-up period of nodes with multiple schedules becomes higher than those of the other nodes, which yields higher energy consumption. Nodes are likely to consume most of their energy in idle state when the traffic load fluctuates, since S-MAC uses fixed duty-cycle. Referring to Fig. 1.a, nodes A, B, and C remain in idle listening when re-activated as long as they do not receive any RTS/CTS packets. If the duty cycle is set to match high traffic load and the network experiences low traffic load, then the node will waste its energy in idle listening. On the other hand, if the duty cycle is low and the traffic load becomes high, then the communication delay will increase. The protocol is appropriate for applications where the traffic load remains constant and predictable. Many other solutions are derived from S-MAC, e.g. T-MAC [9], which provide incremental improvements over this milestone protocol.

IV. Adaptive Duty-cycling Protocols

Adaptive scheduling was introduced to cope with S-MAC traffic fluctuation problem. The key is to interrupt the active mode in the presence of traffic, and to add extra wake up periods in its absence. This makes node duty-cycling adaptation to the traffic load conditions. Compared to static schedules, adaptive ones can reduce latency for heavy traffic load. However, light load traffic may face the early sleep problem with the adaptive schedules. Adaptive schedules can be classified into the following subclasses.

A. Adaptive Grouped Schedule Protocols

In this class, active periods are grouped at the beginning of each frame. These protocols introduce techniques such as, *timeout*, and adaptive listening to sleep when there is no upcoming traffic, [9], [10], [11], [12]. They also add extra wake-up periods when there is more traffic to be sent. T-MAC [9] introduces the timeout (TA) to permit rapid termination of the active period. This may cause the early sleeping problem that causes a break for packet forwarding, as nodes tend to switch quickly to sleep mode. T-MAC uses the *"Future RTS"* technique, as illustrated in Fig. 1.b, which are sent by the next-hop to the third-hop neighbor to prevent its early sleeping. It is likely that T-MAC outperforms S-MAC in surveillance applications [9]. At high traffic loads, and when multiple nodes try to access the channel, some of them have

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to wait for the entire frame. Like T-MAC, AD-MAC [10], MR-MAC [11], and LLM [12] suffer from the early sleeping problem along the path. MRPM [13] copes with the long idle listening of S-MAC. It assumes that by exploiting carrier sensing, nodes at one-hop, two-hop and three-hop on the path toward the sink can overhear the CTS and schedule the future data reception. MRPM is thus able to forward packets only three-hop away for a given winner among contenders, before cycle interruption. Consequently, many packets may miss their ETE delay deadline. DSMAC [14], and Optimized-MAC [15] introduce a similar idea. DSMAC dynamically changes a node's duty-cycle according to the energy and delay requirements. A node increases its duty cycle by adding extra active periods when less latency is required.

B. Adaptive Repeated Schedule Protocols

In this scheme, short active periods are repeated multiple times during each slot. This gives more chance to packets to be forwarded with less contention and minimized delay. SCP-MAC [16] is based on periodic checking for channel activity, with a preamble sampling as a contention resolution mechanism. SCP-MAC synchronizes the wake-up periods of receivers in order to reduce the necessary preamble length. SCP-MAC introduces two contention phases, ($cw1$ and $cw2$, to minimize a chance for collisions. Additional polls are used to lower multi-hop delay in case of burst traffic (Fig. 1.c). Note that since SCP-MAC can only handle one packet per slot, it must use shorter slots than S-MAC and T-MAC to warrant reasonable ETE latency. Furthermore, grouping communications in the synchronized channel polling points increases the probability of collisions in high data rate networks, which inevitably affects the transmission delay.

C. Adaptive Staggered Schedule Protocols

Although repeated schedules give contenders more opportunities to get channel access, they are only efficient for low traffic load. This because a single packet can be forwarded per slot. For further minimization of the per-hop delay, the wake-up time of next hop neighbors must coincide with the transmission time of the node. DMAC [17] addresses this problem by staggering schedules according to the distance from a sink, such that data can quickly flow through from leaves to the sink. DMAC uses *data prediction* and *more-to-send* schemes to avoid interference, conflicts, and simultaneous transmissions from adjacent nodes. The down side of DMAC is that it lacks the flexibility to support communication patterns other than converge-cast. This could be the reason that DMAC never passed the simulation stage. DMAC mainly targets stationary networks, as it does not envisage common global active periods. Thus, dynamic aspects may drastically increase DMAC's delay. LEMR [18] combines SCP-MAC's periodic channel polling with the staggered schedule of DMAC. The key difference is that LEMR's channel polling intervals are shifted according to the distance of the node from the sink. Intermediate nodes do not have to wait for a complete channel polling cycle to forward data. To minimize packet latency, nodes at n hops from the sink periodically poll the channel for δ seconds after the channel polling is performed by nodes at $(n+1)$ hops from the sink, as depicted in Fig. 1.d.

D. Adaptive Reservation Protocols

Staggered schedules may represent the best way to minimize the per-hop latency. However, they may lead to more collisions within the sink's vicinity. To cope with the per-level collision problem, this class of solutions negotiate the periods for to sending and to receiving packets during the reservation window. Nodes thus go to sleep and wake-up at the scheduled time. DW-MAC [19] and SPEED-MAC [20] propose to forward a (SCH) frame over multiple hop route during a data period, and schedules wake-up times for upcoming packets along that route. Every intermediate node along the route sleeps and wakes up at a scheduled time. DW-MAC works under random topology and supports both unicast and broadcast traffic. DW-MAC sets up a one-to-one mapping between data and sleep in such a way that the time, when the scheduling frame is transmitted, determines the corresponding offset of the $DATA$ packet exchange (see Fig. 1.e). Note that although the provided mapping function reduces collision, $DATA$ packet exchange during $sleep$ period must be interlaced by gaps with a size proportional to the $\frac{T_{sleep}}{T_{data}}$ ratio. Furthermore, collisions between data and acknowledgement (ACK) can take place in most of the time, which rises the overall ETE delay.

V. Review Summary and Discussion

The sleep delay is a serious drawback of slotted contention-based MAC protocols. This delay is the time that a node waits until the wake-up of the forwarder at each hop. Many improvements have been proposed to minimize the sleep delay. Static duty-cycled protocols, such as S-MAC, lack flexibility, since nodes follow a common schedule that is fixed in advance and does not change according to the traffic load. Short active periods reduce idle listening but increase contention and collision rate, as well as the latency. On the other hand, long active periods rise idle listening, which affects energy consumption. These protocols can provide only one-hop delay decrease. However, in the presence of cycle interruption, they may result in high ETE delay, especially for multi-hop networks. They are suitable for small networks with predictable traffic load. Adaptive schedule approaches come to cope with the sleep-delay caused by static protocols. They introduce techniques such as timeout (e.g. T-MAC) and adaptive listening (e.g. MRPM). The latter permits long sleep when there is no upcoming traffic, and it adds extra awakings when there is more traffic to be sent. However, because of the early sleep problem, a node is likely to be in sleep state when other nodes need to send data to it. The use of overhearing enables adaptive protocols to keep next hop node awake using signaling packets (e,g, FRTS). Compared to S-MAC, adaptive protocols provide delay decrease by two-hop (T-MAC) and k-hop (MR-MAC), where k depends on the TA duration (timeout). These protocols are still susceptible to cycle interruption like static ones.

Repeated schedule protocols, e.g. SCP-MAC, cope with the early sleep problem and collisions caused by grouped schedule protocols. Small active periods are repeated several times during each slot. This is to give more chance to packets to be forwarded. In SCP-MAC, nodes can only deliver one packet per slot, which still causes cycle interruption. It ensures only k-hops delay decrease for very relaxed traffic load, where k is the number of active periods per slot. Staggered schedules – such as DMAC– try to set the wake-up time of the forwarding nodes in a staggered way, so that a node's active time is partly overlapping with its predecessor and successor active times. However, staggering nodes per-level leads to more contention, and consequently, more collisions. Staggered schedule protocols are more suitable for delay-sensitive applications, since they can ensure ETE delay decrease for very low data rate applications, where traffic in intermediate nodes is not important and collisions due to contentions are less frequent. To cope with per-level collision and multi-hop sleeping problems, schedule reservation has been proposed, e.g. SPEED-MAC. Nodes negotiate packet exchange periods during a reservation window, then they go to sleep and wake up at the scheduled time. However, the negotiation must start from the source to the destination, which makes these protocols more complex, compared to other classes. When the reservation window is big enough to cover all the nodes along the path, ETE delay may considerably decrease.

A. Open Research Directions

Whilst many power-efficient MAC protocols have been proposed, numerous issues related to minimizing the end-to-delay are still wide open. One critical issue with the synchronous wake-up protocols is how to deal with contentions and collisions to minimize the delay. Another important issue is the large idle listening; The synchronous wake-up leads to faster message delivery, but at the cost of more energy consumption due to the longer wake-up. It is still challenging to cope with the sleep delay problem while ensuring adaptability to traffic fluctuation. Combining techniques of asynchronous schemes that provide energy-efficiency, with those of synchronous schemes that minimize the latency, might be a promising approach. Cross-layer design can be useful for delay minimization. For instance, it is possible to use a joined routing and MAC to build a TDMA tree structure, with relaxed synchronization and hybrid access strategy.

VI. Conclusion

Wireless Sensor Networks (WSN) have progressively changed the way to monitor environmental and industrial phenomena over the last two decades. Since these networks use wireless channels, the medium access control is of pivotal importance. Slotted contention-based MAC protocols are widely used for relaxed traffic load conditions in multi-hop WSN. This paper investigates MAC protocols' timeliness. Compared to the traditional classification based on medium access principles, the introduced taxonomy is based on the solutions' mechanisms that affect the delay. Well-known energy efficient slotted contention-based protocols have been discussed from the latency point of view. Our review indicates that some of these protocols can ensure ETE delay decrease, but none of them can provide delay guarantee for time-critical applications.

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