Network-Aware Adaptation of MAC Scheduling for Wireless Sensor Networks

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Abstract

Many recent advances in MAC protocols for wireless sensor networks propose to reduce idle listening. Sending nodes transmit long preambles or repeated advertisements for upcoming packets, thereby allowing their neighbors to have low duty cycles. As these "channel probing MAC protocols" impose a significant drain on the transmitting node, the schedule used for probing should be well matched to the current network conditions. Achieving this requires cross-layer information exchange, which can easily be provided by a new cross-layer information sharing protocol architecture called X-lisa. Our results show that using network-aware adaptation of the MAC schedule provides up to 30% increase in lifetime for different traffic scenarios compared with using fixed schedules.

I. Introduction

Applications for wireless sensor networks are becoming increasingly complex, and they require the network to maintain a satisfactory level of operation for extended periods of time. Because idle listening is a major source of energy dissipation, MAC protocol designs had to be re-thought, and a new generation of MAC protocols (B-MAC [1] and X-MAC [2], among others) were introduced as a result. The sending node occupies the medium to signal its imminent packet transmission for long t_i intervals. Receiving nodes are thus allowed to sleep for at most the duration of this preamble (t_i), and they must stay awake when they sense a busy medium until the packet transfer is complete.

As this paper shows, while a protocol's schedule may reduce energy consumption for unicast packets, it may at the same time waste energy when applied to broadcast packets. Such inefficiencies become significant as broadcast packets make up a larger percentage of the total packets sent on a network. We propose adopting the transmission schedule that yields the best lifetime taken from a pool of compatible protocols.

II. Medium Sampling MAC Protocols

A. Previous Work

B-MAC [1] with Low-Power-Listening (LPL) was the first MAC protocol to introduce channel probing schedules for recent radios. Polastre et al. provide a model for LPL with strong consideration for the target radio. Post-B-MAC protocols include X-MAC [2] and SpeckMAC-D [3]. Both protocols are of the channel probing family and tried to improve the low power listening scheme presented by B-MAC. Further explanation of these protocols is provided in section II-B.

Much work has been dedicated to the task of adapting MAC protocols to conditions in the local neighborhood of a node. The authors in [4] aim to adapt the data rate for packet transmissions based on channel quality predictions in high-rate WPANs. The intended destinations of a prospective sender are notified through *rate-adaptive ACK* frames.

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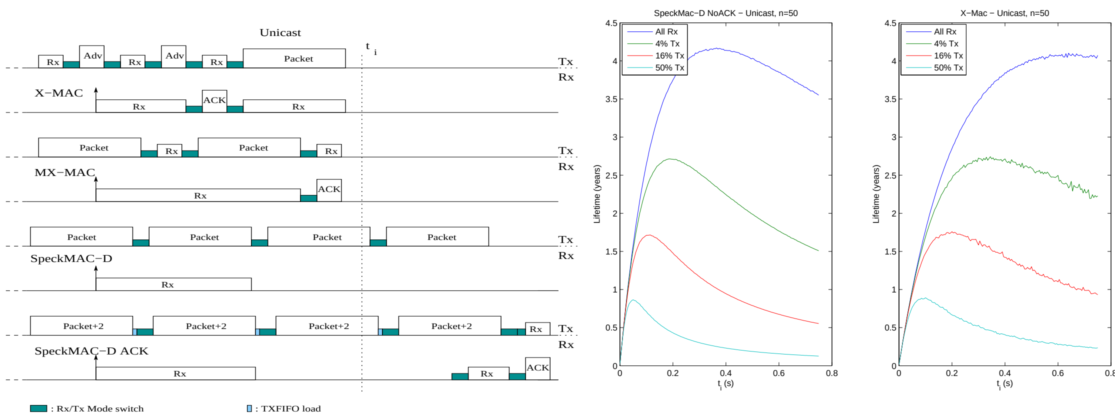


(a) (b)

Fig. 1. (a) X-MAC, MX-MAC, SpeckMAC-D and SpeckMAC-D-ACK protocol timelines for unicast. t_i is the channel check interval. (b) Optimal t_i for SpeckMAC-D and X-MAC as a function of the number of received and transmitted packets.

B. The Protocols

X-MAC and SpeckMAC-D were introduced around the same time and follow the same basic principle. These protocols differ only in their schedule. Figure 1(a) provides a detailed protocol timeline for X-MAC, MX-MAC (our proposed modifications to X-MAC), and SpeckMAC-D. X-MAC repeatedly sends an advertisement packet to announce it has data to transmit. The intended receiver replies with an ACK and stays on until the data transmission is complete. X-MAC does not provide guaranteed data delivery, as the ACKs are for the advertisement messages rather than for the data itself. Thus we propose MX-MAC, which repeatedly sends the data packet, instead of advertisements, until the receiver ACKs the packet. SpeckMAC-D follows the same principle, but cannot be interrupted by an ACK, and thus packet repetition continues throughout the t_i time. SpeckMAC-D-ACK designates a schedule that allows a receiver to wake up at the end of the packet stream and send an ACK to verify receipt of the packet.

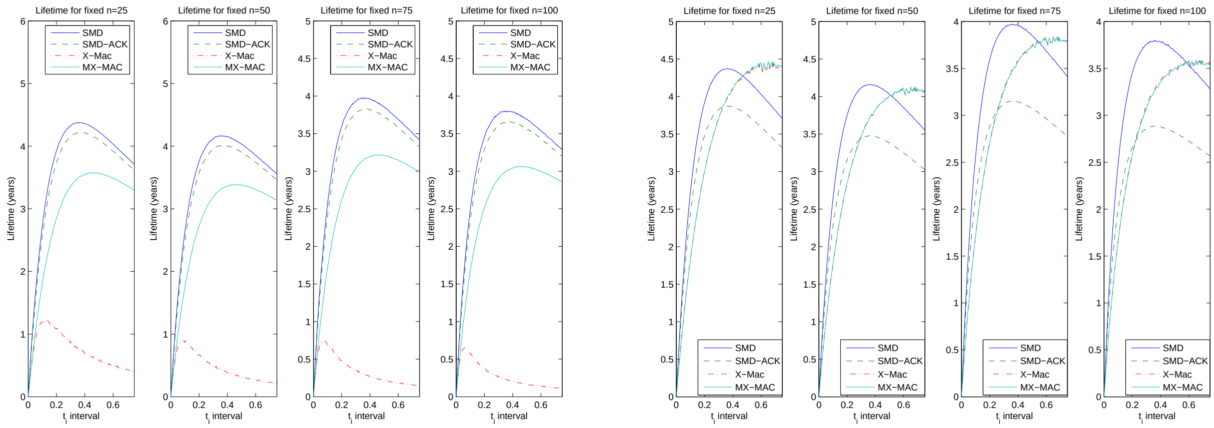
C. Effects of Parameters on the Channel Probing Interval t_i

The parameter t_i may take different values in different regions of the network. Obviously, in such cases, two nodes communicating with each other need to share their value of t_i. Longer t_i values favor receiving nodes since a packet is almost always available (in both X-MAC and SpeckMAC-D) when they wake up. On the other hand, a longer t_i has the opposite effect in sending nodes since more packet repeats have to be sent (for a fixed packet size). While the number of neighbors (and their cumulative energy) is a good indication of a node's importance to the network as a whole, it is not a sufficient parameter to determine t_i because of adverse effects on sending and receiving nodes' lifetimes. Figure 1(b) shows that the optimal t_i value varies with the ratio of received packets vs. sent packets. A MAC protocol may elect a t_i value that corresponds to its optimal given its current percentage of received packets. Further thought also has to be given to contention, which is a possible consequence of increasing t_i.

D. Adapting the Packet Transmission Schedule

All packets do not have the same importance for the network or for the application. While other protocols higher in the stack may reorder or suppress outgoing packets, the focus of this paper is the MAC / data link layer. We propose integrating the following rules to any channel probing MAC protocol:

- Packets marked as urgent should be handled immediately, while other packets may be sent only at the scheduled wake-up time.



(a) (b)

Fig. 2. Node lifetime for X-MAC, MX-MAC, SpeckMAC-D and SpeckMAC-D-ACK with a fixed n. (a) Broadcast packets (b) Unicast.

- Service packets, even though they may not be urgent, should precede non-urgent data packets.
- If a packet is part of a burst, the node should transmit subsequent packets immediately.

E. X-lisa: A Cross-Layer Information Sharing Architecture

As discussed above, the X-MAC and SpeckMAC-D protocols may benefit from adapting their schedules and t_i values according to different criteria. These improvements all require that the MAC protocol have information not normally ascribed to the MAC layer and not easily obtained using conventional protocol architectures. One architecture that can facilitate this type of cross-layer information sharing is X-lisa [5]. X-lisa is a new architecture that enables adaptation at all protocol levels by gathering and sharing information about key parameters in the node and its local neighborhood.

III. Comparison of MAC Protocol Scheduling Techniques

A. Performance Comparison

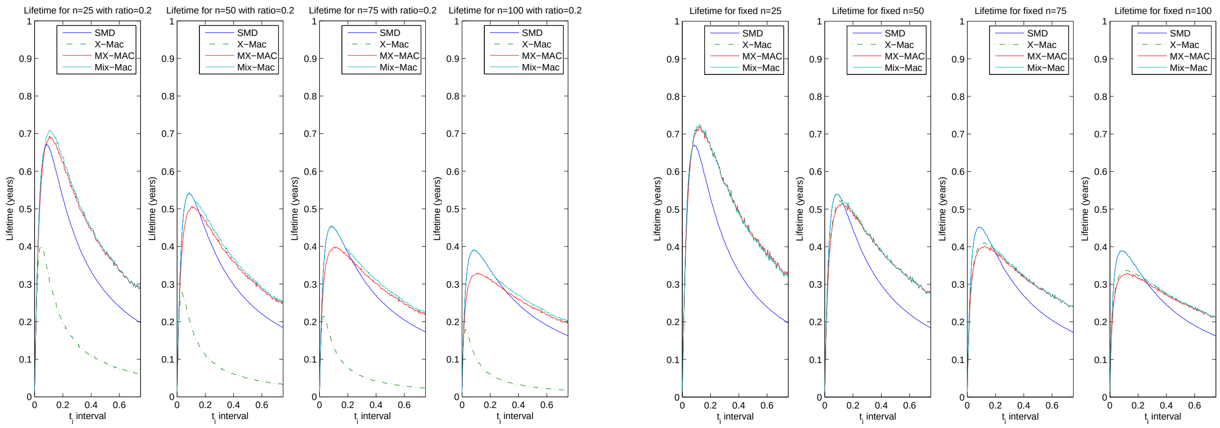
We compare X-MAC, MX-MAC, SpeckMAC-D and SpecMac-D-ACK for a scenario similar to the one described in [1]. One node receives packets at a rate r from n neighbors. This node sends m packets to a neighboring node.

Figure 2 provides a detailed evaluation of the MAC protocols for broadcast and unicast packets. In general, SpeckMAC-D performs better than all the other protocols in the broadcast case. X-MAC suffers from setting its radio in receive mode (more costly in the CC2420) for longer periods of time.

For unicast packets, SpeckMAC-D, in spite of repeating data packets for at least t_i seconds without interruption, brings a lifetime comparable to the X-MAC protocols. Note that the optimal lifetime for SpeckMAC-D is achieved for smaller values of t_i such that a sending node would spend much less time in Tx mode. Two observations should be made: the optimal value of t_i is a narrow "sweet spot" and the burden of acknowledgment is put on upper layers (not included here). Other parameters such as packet size and ratio of n over m influence the relative performance of all the protocols.

B. MiX-MAC: Adapting the MAC Schedule to Conditions in the Network

1) Picking the right MAC schedule: The previous section has shown the need for a MAC protocol whose performance is not compromised by the fact that this is a broadcast/unicast packet. This is accomplished



(a) (b)

Fig. 3. Node lifetime as a function of t_i for MiX-MAC, X-MAC, MX-MAC and SpeckMAC-D. The packets are 20% broadcast / 80% unicast (a) and all unicast (b), sent at a rate $r = \frac{1}{10}$.

through MiX-MAC, a protocol that adopts the most energy efficient schedule within a pool of compatible protocols and uses the rules set forth in section II-D.

The MiX-MAC protocol adopts SpeckMAC-D's schedule for broadcast packets, and for unicast packets, it uses four axes to decide the appropriate schedule. These include t_i value, packet size, estimated ratio of transmitted vs. received packets, and the ACK requirements determined by the upper level protocols or services. A small look up table within MiX-MAC helps in deciding what schedule is best suited for the current node, network and application conditions. The threshold values dictating a change in the MiX-MAC schedule can be established before deployment. Note that receivers do not need to be made aware of any changes in the transmitter's protocol, as the receiver behaves the same for all the protocols and can differentiate the transmitter's current protocol once the packet is received.

2) Resulting lifetime increase: Figure 3 presents a comparison of the lifetimes for MiX-MAC, X-MAC and SpeckMAC-D for a packet size of 40 bytes, 20% of the total traffic being broadcast packets (all other packets are unicast) (Figure 3(a)) and all unicast packets (Figure 3(b)). The rate r is $\frac{1}{10}$. These results show that MiX-MAC achieves the upper bound of node lifetime by selecting the best schedule for various scenarios. X-MAC suffers greatly in broadcast mode, even for relatively small proportions of broadcast packets (20%). MiX-MAC helps the MAC protocol obtain the best of all worlds: lifetime gains are obtained over other protocols on a full range of t_i values. This last point is important because in a network where the rate of packet transmissions varies, the optimal value of t_i would naturally vary.

IV. Conclusions and Future Work

In this paper, we propose adapting the MAC schedule to node and network conditions to improve performance under a wide range of conditions and for both unicast and broadcast packets. The MAC schedule should be chosen to maximize the lifetime of the network, which includes reducing contention. Utilizing this information at the MAC level (via the MiX-MAC protocol) is made possible through use of the X-lisa architecture, which provides vertical (the node's) and horizontal (the neighbors') information to all protocols in the stack.

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