

ENERGY-AWARE WIRELESS SENSOR NETWORKS MAC MODELLING AND SIMULATION WITH EFFICIENT TRANSCEIVERS

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ABSTRACT

This paper addresses an analytical model that may be applied to different Wireless Sensor Networks (WSNs) Medium Access Control (MAC) protocols using different efficient transceivers. Our model accounts for the impact of several simultaneous factors, including periodic receive/transmit and sleep cycles, the length of the transmitted packet and data rate. The Sensor Block Acknowledgement MAC, a new innovative WSNs MAC protocol that uses a Block Acknowledgement scheme to achieve energy efficiency, is proposed as well. Our implementation takes into account the average delay, which can be clearly reduced when a Block Acknowledgement Scheme is used. In terms of energy consumption and average delay the efficient radio transceivers that operate in the 2.4GHz band have better results than the ones that use the 900MHz band. Adaptive listening (AL) enables radio transceivers to stay alert after the communication between two neighbour nodes before going to sleep, allowing for energy saving when synchronisation is involved.

I INTRODUCTION

The very low energy consumption is a mandatory characteristic of Wireless Sensor Networks (WSNs) because there are strong limitations to power supply WSN tiny devices. One of the most important power consumers in the sensor nodes is the radio transceiver. To achieve energy-efficiency, medium access control (MAC) protocols are used, enabling to determine and change the operation mode of the radio. Furthermore, devices must cooperate among themselves in order to efficiently exchange data, by using multi-hop to save energy. For example appropriately randomizing the data while performing a reverse-multicast scenario, it is assumed that all nodes need to have a path to a single destination through the network toward a given sink. As a consequence, an efficient management of transmission, reception, and sleep modes of operation should be implemented in each individual WSN device. WSN devices must remain in sleep mode whenever they do not have to receive/process/transmit data packets. Efficient energy-aware protocols are therefore crucial to ensure error free robust packet delivery whilst minimizing power consumption. The well-known Sensor-MAC (S-MAC) protocol [1] tries and reduce the energy consumption by introducing periodic listen and sleep cycles. It performs access control and reduces the energy consumption by synchronising nodes based on scheduling sleep/listen cycles, called frames, between neighbouring nodes [1]. It tries to eliminate the four sources of energy waste: collisions, overhearing, protocol overhead and idle listening. Each

node alternates between a fixed-length listening period and a fixed-length sleep period according to its schedule. S-MAC divides the time frame into two parts: the listening and sleep periods. The listening period is used to coordinate the nodes that have data to send/receive. The sleep period is used to deactivate some of the functionalities of the nodes, e.g., turn the transceiver off in order to save energy. In the past years, several analytical models have been proposed to analyze the impact of sleep on the network performance in WSN [2]. By using our model, we intend to study the impact of different radios transceivers in the energy consumption when using S-MAC protocol whilst investigating the impact on energy consumption when using Sensor Block Acknowledgement MAC (SBACK-MAC) protocol that improves channel efficiency by aggregating several acknowledgement (ACK) packets into one special frame. The analysis of SBACK-MAC performance in terms of latency and power consumption in the context of adaptive listening (AL), a concept proposed in [1] for S-MAC, is also a challenge. The remaining of this paper is organized as follows. Section II presents a possible State Transition Diagram (STD) that describes the S-MAC protocol, as well as SBACK-MAC. Section III presents the SBACK-MAC in detail. Section IV presents the simulation results for S-MAC and SBACK-MAC (in the absence and presence of AL). Finally, Section V presents the conclusions.

II S-MAC: RELATED RESEARCH

One possible STD for the S-MAC protocol is shown in Fig. 1. It describes the states, events and actions. The STD for SBACK-MAC consists of twelve states. It includes the eleven states from the S-MAC protocol.

When multiple nodes intend to transmit the data in a shared medium there is a contention. In order to decide which wireless node gains access to the shared medium an efficient MAC layer must be implemented. It uses carrier sensing information from the radio transceiver. The possible medium access states are the following:

- **Free:** Medium is free, there is no ongoing transmission;
- **Busy:** Medium is not free, there is an ongoing transmission.

When a node has data to transmit/receive, two possible states are considered for its queue:

- **Not empty:** n packets are waiting for transmission;
- **Empty:** The buffer is empty.

Note that the S-MAC and SBACK-MAC protocols have different behaviour when the node has broadcast and unicast data packets to transmit.

START: the node will “turn on”; **WAIT SYNCH:** the node is waiting for SYNCH packets; **SYNCH:** the node will try to synchronise with neighbour nodes; **SLEEP:** the node will “turn off” the radio; **BACKOFF SELECT:** the node will select a “backoff time”; **BACKOFF:** the node will activate the “backoff time”; **IDLE:** the node is idle, waiting for a task to perform; **NAV_SLEEP:** the node goes to sleep until the end of the ongoing transmission; **TRANSMIT:** the node will transmit the frame; **VERIFY FRAME FINISH:** the node will verify if the frame was correctly transmitted; **WAIT RESPONSE:** the node will wait for confirmation of a successful transmission.

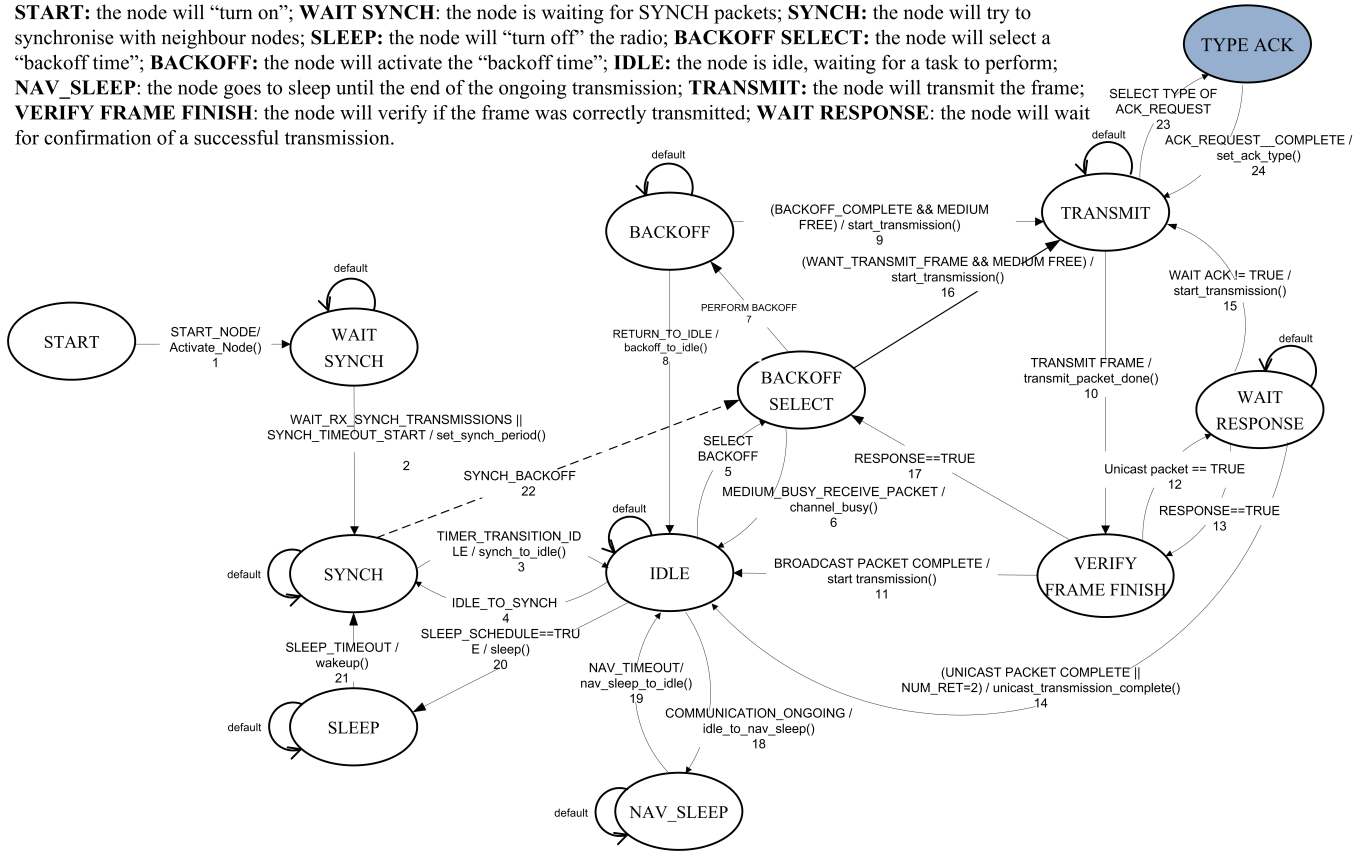


Figure 1: S-MAC and SBACK-MAC State Transition Diagram.

III SBACK-MAC PROTOCOL

Based on S-MAC, we developed an innovative MAC protocol that uses block acknowledgment (BACK) mechanism like the authors from [3], the SBACK-MAC protocol. The SBACK-MAC protocol, has some of the characteristics of the “well known” S-MAC protocol. It is basically a protocol based on a duty cycle scheme. It tries to reduce the major sources of energy waste, such as collisions, overhearing, idle listening and control packet overhead. The way SBACK-MAC treats the ACK control packets is the main difference comparatively to S-MAC. A BACK mechanism is proposed that improves channel efficiency by aggregating several ACK control packets into one special frame called *Block ACK Response*. Hence, an ACK packet will not be received in response to every data packet sent. This way, power consumption will be significantly reduced when a series of data messages needs to be transmitted. As several ACK control packets (one for each data packet) are not transmitted/received anymore, the extra energy waste caused by this overhead is avoided. Fig. 1 illustrates the STD for the SBACK-MAC protocol, by considering the TYPE ACK state that will be responsible to activate the BACK mechanism. The BACK mechanism improves channel efficiency by aggregating several acknowledgments into one special frame called *Block ACK Response*. In our proposal, the BACK mechanism is initialized by the exchange of the following two special packets: *RTS ADDBA Request* and *CTS ADDBA Response*. ADDBA

is the acronym for “Add Block Acknowledgment”. The structure of the packets is presented in Fig. 2 a).

| | | | | | |
|---------------|--------|------------------|--------|------------------|--------|
| Type | Length | Type | Length | Type | Length |
| Duration | CRC | Duration | CRC | Duration | CRC |
| Sender Node | | Sender Node ID | | Sender Node ID | |
| Receiver Node | | Receiver Node ID | | Receiver Node ID | |
| | | Packets Sent | | Packets Received | |
| a) | | b) | | c) | |

Figure 2: a) *RTS ADDBA Request* and *CTS ADDBA Response*, b) *Block ACK Request* and c) *Block ACK Response* packets format.

After initialization, data packets may be transmitted accordingly from the sender to the receiver nodes. In our implementation, the number data packets sent are limited to 100 (10 messages fragmented into 10 small data packets). When the sender has no more data to transmit, it will send a special packet, called *Block ACK Request*, in order to inquire the amount of packets successfully delivered to the receiver. In response the receiver will send a special packet called *Block ACK Response* that is responsible to identify the packets that were not received properly and require retransmission. The structure of these packets is presented in Figs. 2 b) and 2 c).

Finally, when the sender receives the *Block ACK Response* it will send a *RTS DELBA Request* to the receiver indicat-

ing that the *Block ACK Response* was successful received and concludes the BACK mechanism. *DELBA* stands for “Delete Block Acknowledgment”. Then, the receiver will send a *CTS DELBA Response*, and the BACK sequence is complete. The structure of the *DELBA* packets is the same presented in Fig. 2 a). A message sequence chart for the BACK sequence is shown in Fig. 3, based on [3].

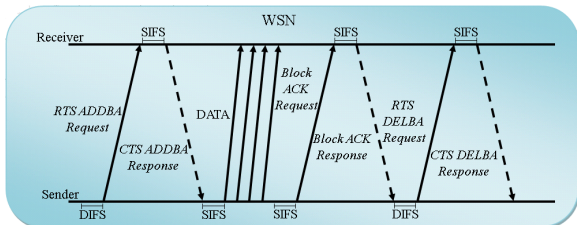


Figure 3: SBACK-MAC BACK sequence.

IV SIMULATION EVALUATION

IV.A Scenario

By minimising the number of the state transitions, the energy spent on the transceiver state is minimized. A two-hop network topology, with two sources and two sinks, was considered. An OMNeT++ [4] experimental simulation setup was used. Packets flow from source node 1, through node 0, to sink node 3, while the packets originated by source node 2 flow, through node 0, to reach sink node 4. This topology is a simple star topology where node 0 acts as a central node, a very common topology in healthcare applications [5]. In our experimental scenario there are four regular nodes, and one special node (node 0) which will act as a gateway. The nodes may only communicate with direct neighbours.

In the simulation setup a time of 900 s of network lifetime was considered in order to switch between the different states presented in Fig. 1, whilst incorporating all the computations related with energy consumption and delay. In this first set of simulations, we considered several runs with five different random seeds, and a 95% confidence interval.

IV.B S-MAC Protocol: Model for the Energy Consumption

In the first set of tests for S-MAC protocol, we have considered the TR1000 radio transceiver from RF Monolithics, Inc. [6], which operates at 900MHz. Table 1 shows the power consumption specifications for this transceiver, where P indicates the power spent by each state.

Table 1: TR1000, CC2420 and AT86RF230 Specifications

| Parameter | TR1000 | CC2420 | AT86RF230 |
|------------------|---------|--------|-----------|
| P_{Sleep} | 0.015mW | 60nW | 60nW |
| $P_{Receive}$ | 13.5mW | 59.1mW | 46.2mW |
| $P_{Transmit}$ | 24.75mw | 52.2mW | 49.5mW |
| Data Rate [kb/s] | 19.2 | 250 | 250 |

The power consumption in the source nodes depends on

the power consumption in the different states of the radio transceiver. To confirm the practical experimentations an energy model was conceived as follows:

$$E = P_{Transmit} \times T_{Transmit} + P_{Receive} \times T_{Receive} + \dots + P_{Sleep} \times T_{Sleep} \quad (1)$$

The time a radio will be in the transmit mode is given by:

$$T_{Transmit} = Packet\ Size / Data\ Rate \quad (2)$$

where, $PacketSize=38B$ (6B Header, 30B Payload and 2B CRC).

The time the radio will be in the receive or sleep mode is given by:

$$T_{Receive} = T_{Sleep} = Message\ Inter-Arrival\ Period \quad (3)$$

where, *Message Inter-Arrival Period* indicates the time needed to generate a new message.

Fig. 4 presents the variation of the energy consumption as a function of the message inter-arrival period originally obtained experimentally (in hardware), in [7], for the TR1000 transceiver (solid blue line) and S-MAC protocol. It also presents the curve for the S-MAC protocol without ACK control packets, obtained by applying equations (1), (2) and (3) and running simulation results for the protocol (red dotted line).

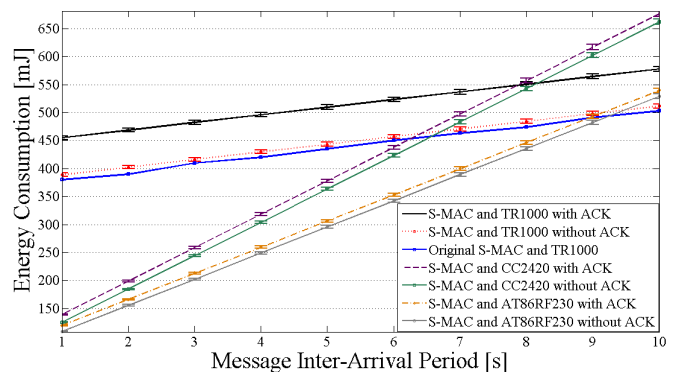


Figure 4: S-MAC energy consumption for TR1000, CC2420 and AT86RF230 transceivers.

Like in [1], we considered that each source node sends a total of 100 data packets. The original experimental values for the S-MAC energy consumption results, from [7], and the ones obtained by simulation are very similar, Fig. 4. Based on these results, it is possible to extrapolated this model for two different radios transceivers operating in the 2.4GHz band: the CC2420 [8] and AT86RF230 ones [9], whose characteristics are also presented in Table 1.

These results were obtained for the TR1000, CC2420 and AT86RF230 radio transceivers by simulation. The 95% confidence interval is also shown. As shown in Fig.4, when the message inter-arrival period is less than 7 s, the AT86RF230 energy consumption is the lowest one, followed by the one of the CC2420 transceiver. Besides as, the TR1000 transceiver supports the lowest data rate for a given message inter-arrival

period it has the worst performance, as data transmission takes longer time, TR1000 will be active for a longer time period.

For an inter-arrival period between 7 and 9 s, AT86RF230 still shows the lowest energy consumption, followed by the TR1000 transceiver, while the CC2420 has the worst performance. As, the message inter-arrival period is longer, the negative impact of the lowest data rate becomes irrelevant and the TR1000 has the best performance (when compared with CC2420), is it needs less energy to transmit/receive. Finally, when the message inter-arrival period lays between 9 and 10 s, AT86RF230 and TR1000 show approximately the same energy consumption. However, the value for the energy consumption in the AT86RF230 is slightly higher. In this case, the CC2420 transceiver has the worst energy consumption performance.

The actual S-MAC operation involves the use of ACK control packets, every packet sent by the transmitter and correctly received by the receiver requires an ACK response. The transmitter will waste energy not only by sending the data packet, but also receiving the ACK control packets. Therefore, the energy model previously presented must take into account the energy spent to receive an ACK packet:

$$E_{ACK} = P_{ReceiveACK} \times T_{ReceiveACK} \quad (4)$$

The time a radio is in the receiver mode (to receive an ACK packet) is given by:

$$T_{ReceiveACK} = Packet\ Size / Data\ Rate \quad (5)$$

where, $Packet\ Size=8B$ (6B Header and 2B CRC).

When a node receives an ACK packet, it needs to process less 30B than in the case of a data packet. The energy consumption in the source nodes for the case when they also need to process the ACK packets is presented in Fig. 4. The energy consumption slightly increases relatively to the case where no ACK packets are used, mainly for the TR1000 transceiver.

IV.C SBACK-MAC protocol

The SBACK-MAC protocol improves application-level performance by using the message passing scheme where messages are divided into small fragments. All these fragments are then transmitted in a single burst, starting by the exchange of *RTS ADDBA Request/CTS ADDBA Response* packets between nodes. When this exchange is finished, the wireless medium is reserved during the time needed to complete the transfer of the entire fragmented message. Furthermore, the duration field of each fragment carries the time needed to transmit all the subsequent fragments, plus the *Block ACK Response* that will be send after the end of all data messages.

In S-MAC, every packet correctly received by the receiver requires an ACK response. The transmitter will waste energy not only sending the data packet but also receiving the ACK control packets. Therefore, the energy model previously presented must take into account the energy spent to receive an ACK packet. In SBACK-MAC, the use of ACK control packets is reduced, since these not have an ACK response packet for every DATA packet sent. Instead, one special packet, called *Block ACK Response* will be used at the end of the transmission of all data packets. This packet informs the sender of how

many packets were correctly received by the receiver. By reducing the number of ACK control packets we intend to reduce the nodes' power consumption. Hence, more useful data packets may be transmitted.

Fig. 5 presents the source nodes energy consumption as a function of the message inter-arrival period when ACK or BACK mechanisms are used for the TR1000, CC2420 and AT86RF230 transceivers.

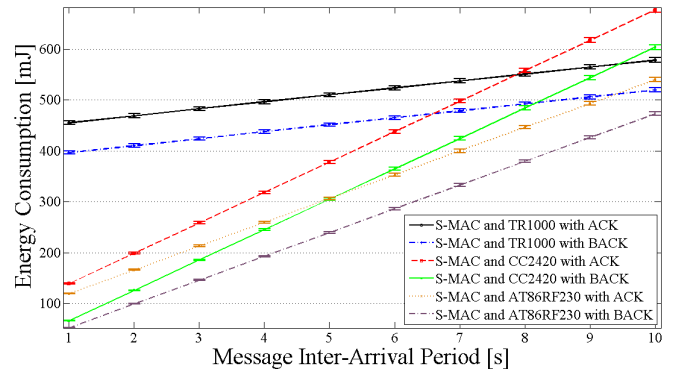


Figure 5: Energy consumption for the TR1000, CC2420 and AT86RF230 transceivers with simple ACKs or BACKs.

Fig. 6 presents the energy saving in percentage for the SBACK-MAC protocol (compared to the simple S-MAC with ACK). When the message inter-arrival period increases from 1 to 10 s, the energy saving varies:

- From 12.88 to 10.14 % for the TR1000;
- From 52.58 to 10.81 % for the CC2420;
- From 55.95 to 12.38 % for the AT86RF230.

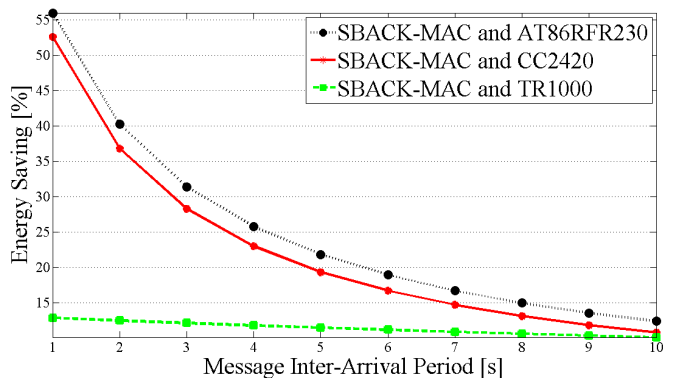


Figure 6: Percentage of energy saving for the TR1000, CC2420 and AT86RF230 transceivers with the BACK mechanism.

As shown in Fig.6, AT86RF230 has the best performance in terms of energy saving when compared with the TR1000 and CC2420 transceivers. TR1000 is the worst transceiver in terms of energy saving, although the increase of the message inter-arrival period has less impact when comparing with the other two transceivers.

IV.D Presence of adaptive listening

In multi-hop networks, it is important to study the impact of energy consumption and delay in data packets transmitted/received. We have compared and analysed the curves for latency between S-MAC and SBACK-MAC protocols in the absence and presence of the adaptive listening (AL) mechanism presented in [1]. The AL mechanism proposed in [1] facilitates to virtually increased the duty cycle of sensor nodes putting them in a more active mode when network traffic increases. The primary objective is to achieve higher throughput whilst decreasing the delay (latency). Based in the formulations from [1] we have compared the curves for the latency between S-MAC and SBACK-MAC protocols, in the absence and presence of the AL mechanism. A linear topology network with 11 nodes (like the one presented in [1]) was considered. The packets from source node 1 flow, through node 2, and so on, until they reach node 11. We considerer that each node sends 10 messages, which are fragmented into 10 small data packets (a total of 100 messages is send by each node). Fig. 7 presents the achievable results. S-MAC in the absence of sleep cycles with ACK is the optimal protocol, whose latency has the asymptotic behaviour for the set of S-MAC/SBACK-MAC protocol with ACK we are analysing. It is shown in Fig. 7 that the curve for S-MAC with AL is close to the average latency of S-MAC in the absence of sleep cycles with ACK. Results also show that the latency for SBACK-MAC in the presence of AL with ACK is slightly lower (~ 0.7 s) than for S-MAC in the presence of AL with ACK. This shows the ability of SBACK-MAC to adapt to different topologies.

Moreover, the curve for the latency of SBACK-MAC in the presence of AL in terms of latency is approximately equal although is higher to the one of S-MAC in the presence of AL with no ACK control packets. With shows the potential of the BACK mechanism. This is explained by the fact that only 6 extra control packets need to be transmitted beyond the normal data transmission (with no ACK) in the presence of a BACK mechanism as shown in Fig. 3.

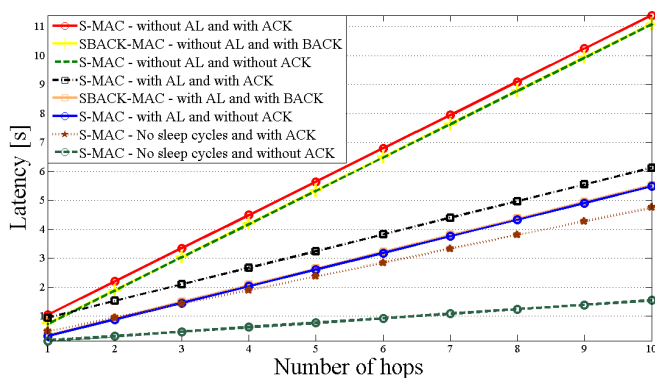


Figure 7: Mean Latency on each hop.

The results also show that in communications involving both duty cycle protocols (as S-MAC or SBACK-MAC) and ACK control packets, SBACK-MAC always outperforms the S-MAC protocol (with normal ACK) in terms of delay.

V CONCLUSIONS

Radio transceivers in the 2.4GHz band usually present lower energy consumption. This characteristic is more noticeable when the message inter-arrival time is shorter. The analytical model for the energy consumption of TR1000 was extrapolated to different radio transceivers, operating at 900 MHz and 2.4GHz, based on validation of the results originally obtained for the experimental energy consumption (in hardware) in [7].

The use of a BACK mechanism improves channel efficiency by aggregating several ACK into one special frame called Block ACK Response. This aims to reduce the power consumption by transmitting less ACK control packets and by decreasing the time periods the transceivers should switch between different states. The analysis of the SBACK-MAC protocol with adaptive listen shows that the use of a BACK mechanism results in a decrease of the latency when ACK control packets need to be transmitted. Moreover the performance of SBACK-MAC with sleep cycles i) is the same as S-MAC in the presence of AL without ACK, and ii) is very similar to S-MAC without sleep cycles and with ACK, showing that in terms of latency this protocol could be a valid possibility in a multi-hop network. These results clearly shows the potentialities of SBACK in multi-hop networks in contention environments. Further work is needed to simulate the actual behaviour of SBACK-MAC and to verify if it appropriately adapts to different topologies.

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