Adaptive Radio Modes in Sensor Networks: How Deep to Sleep?

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Abstract—**Energy-efficient performance is a central challenge in sensor network deployments, and the radio is a major contributor to overall energy node consumption. Current energy-efficient MAC protocols for sensor networks use a fixed low power radio mode for putting the radio to sleep. Fixed low power modes involve an inherent tradeoff: deep sleep modes have low current draw and high energy cost and latency for switching the radio to active mode, while light sleep modes have quick and inexpensive switching to active mode with a higher current draw. This paper proposes adaptive radio low power sleep modes based on current traffic conditions in the network, as an enhancement to our recent RFIDImpulse low power wake-up mechanism. The paper also introduces a comprehensive node energy model, that includes energy components for radio switching, transmission, reception, listening, and sleeping, as well as the often disregarded micro-controller energy component to evaluate energy performance for both MicaZ and TelosB platforms, which use different MCU's. We then use the model for comparing the energy-related performance of RFIDImpulse enhanced with adaptive low power modes with BMAC and IEEE 802.15.4 for the two node platforms under varying data rates. The comparative analysis confirms that RFIDImpulse with adaptive low power modes provides up to 20 times lower energy consumption than IEEE 802.15.4 in low traffic scenario. The evaluation also yields the optimal settings of low power modes on the basis of data rates for each node platform, and it provides guidelines for the selection of appropriate MAC protocol, low power mode, and node platform for a given set of traffic requirements of a sensor network application.**

I. INTRODUCTION

Energy-efficient performance is a central challenge in sensor network deployments, as battery replacement is costly and often difficult in inaccessible deployment regions. Several efforts have addressed the energy efficiency, through the design of energy saving MAC protocols, such as duty cycling protocols [4] or low power wake-up radio protocols [9], and routing protocols, such as [8].

Radio energy consumption is a major component contributing to the overall energy consumption at each node. Current MAC protocols put the radio in sleep mode while there is no data to send or receive, in order to minimize energy consumption. Although common radios for sensor networks support multiple sleep modes, the radio sleep mode in current MAC protocols is static. Choosing a static low power mode involves an energy and delay tradeoff. For example, the CC2420 [3] radio provides three different radio low power modes. The deepest sleep mode, which turns off the oscillator and voltage regulator, provides the lowest current draw of all low power modes. However, it also involves the highest energy cost and the longest latency for switching the radio back to active mode. In contrast, the lightest sleep mode provides a transition to active mode that is quick and energy inexpensive, but it has a higher current draw. In a low traffic scenario, it is better to use the deep sleep mode as nodes spend more time sleeping than switching back and forth between sleep mode and active mode. In a high traffic scenario, a lighter sleep mode is more suitable as the cost of switching the radio frequently into deep sleep mode would exceeds the energy saving of the deep sleep mode's low current draw.

To address this tradeoff, this paper proposes adaptive radio low power sleep modes that dynamically change according to current traffic conditions in the network. To demonstrate the benefits of adaptive sleep modes, we incorporate them into our recently proposed RFIDImpulse mechanism [12], which uses RFID tags as an out-of-band wake up radio for sensor networks [1], [11], and compare its performance against the popular BMAC [4] protocol and the IEEE 802.15.4 standard [14] across two pervasive sensor node platforms, namely MicaZ [6] and TelosB [7].

The performance evaluation of proposed protocols generally considers the radio energy consumption, including receiving, transmitting, listening, and sleeping energy consumption components, but it disregards the switching energy component [13] that is appreciable for any protocol that switches nodes between active and sleep modes in low traffic conditions. While in some cases protocol evaluations consider the sensor energy consumption, they also often ignore the energy consumption at the micro-controller unit (MCU). Disregarding MCU power consumption typically stems from two assumptions: (1) that sensor networks are homogeneous and use the same node platform, in which case the MCU power component does not affect relative power consumption among nodes or protocols; and (2) that MCU power consumption is negligible relative to radio power consumption. However, MCU power consumption becomes relevant for heterogeneous sensor networks that include multiple node platforms or for choosing suitable node platforms and protocols for a particular application scenario.

In order to determine how to adapt low power modes in RFIDImpulse and to compare the MAC protocols fairly across different platforms, this paper presents a sensor node energy consumption model that includes switching energy and micro-controller energy components. The model enhances existing models [4], is generalizable to any MAC protocol and node platform, and serves as the basis for the performance

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evaluation in this paper. For the evaluation, we have measured the current draw of the CC2420 radio, which is used in both TelosB and MicaZ, in each of it operating modes, and we use the *measured* values for comparing the protocols. The comparison of the protocols yields guidelines for selecting appropriate MAC protocols and node platforms for specific traffic requirements of an application. We also determine the optimal radio low power mode within RFIDImpulse as the data rate varies.

In sum, the novel contributions of this paper are four-fold:

- Proposal of adaptive radio low power sleep modes within our previously proposed RFIDImpulse protocol that can dynamically change based on network or node traffic
- Introduction of an analytical energy model that considers radio energy consumption, including transmission, reception, listening, sleeping, and switching energy components, and micro-controller energy consumption as an enabler for comparing protocols across node platforms that use different processor boards.
- Energy-efficiency evaluation of BMAC, IEEE 802.15.4, and RFIDImpulse across 2 popular node platforms, MicaZ and TelosB. The evaluation considers the dependence of energy-efficiency and optimal low power mode on data rate.
- Provision of guidelines based on the evaluation results for MAC protocol, power mode, and node platform selection according to the expected traffic requirements of the target application.

The remainder of the paper is organized as follows. Section II presents the details of BMAC, IEEE 802.15.4 and the adaptive low power mode version of RFIDImpulse, while Section III provides the analytical model for evaluating the energy benefits of the three protocols. Section IV evaluates the performance of the three protocols for MicaZ and TelosB in a multi-hop network, and section V discusses the results and concludes the paper.

II. MAC PROTOCOLS

This section presents the three protocols under consideration separately: BMAC, IEEE 802.15.4 and RFIDImpulse.

A. BMAC

BMAC [4] is an asynchronous and lightweight sensor network MAC protocol that aims at providing versatile medium access while keeping the MAC functionality as simple as possible. As an asynchronous protocol, BMAC eliminates the communication and processing overhead for scheduling and synchronization, which reduces energy consumption. BMAC enables each node to wake up periodically to check for channel activity. The wake-up period is referred to as the check interval. BMAC defines 8 check intervals, and each check interval corresponds to one of BMAC's 8 listening modes. To ensure that all packets are heard by neighboring nodes, packets are sent with a preamble whose reception time is longer than the check interval. BMAC therefore defines 8 different preamble lengths referred to as transmit modes. Although several optimizations have improved over BMAC since its release, we consider it here as it remains the building block of low power listening in TinyOS-1.x.

B. IEEE 802.15.4

The IEEE 802.15.4 standard [14] provides MAC and PHY layer specifications for low data-rate and energy-efficient wireless networks. The MAC layer specifications include a beacon-enabled mode and a non-beacon enabled mode. The beacon-enabled mode represents an overkill and does not perform well in long-term monitoring application, so we focus here on the non-beacon enabled mode. In non-beacon enabled mode, no beacons are broadcast, so 802.15.4 reduces to plain CSMA/CA.

Nodes use a binary exponential back-off mechanism to resolve collisions, with the variable BE defining the number of slots during each back-off period. Figure 1 shows the backoff structure of 802.15.4 with BE initially set to 3. Thus, any node with data to send selects a random time slot R_1 during the first $2^{BE} - 1 = 7$ time slots. The node then performs a clear channel assessment (CCA) during the timeslot R_1. If it detects no activity on the channel, then the node assumes the channel is free of carriers, so it reserves the channel for this time slot. Otherwise, if the channel is busy during time slot R_1, then the node backs off, increments BE by 1, and selects a random time slot R_2 during the next $2^4 - 1 = 15$ time slots. The CCA process is repeated, and in case R_2 is also busy, then the node repeats the process again for BE=5 to select R_3. If R_3 is free, then the node sends its data during R_3. Otherwise, it drops the packet.

C. RFIDImpulse

RFIDImpulse is a very low power radio wake-up scheme for sensor networks that relies on off-the-shelf RFID readers and tags. The basic functionality of RFIDImpulse is shown in Figure 2. All network nodes turn off their radios, including the voltage regulator and the oscillator, as long as they have no packets to send or receive. The nodes also put their micro controller units (MCU) in power down mode during this idle period. A node that wishes to send a packet uses a built-in RFID reader to trigger an RFID tag that is located at the remote sensor node. The impulse from the sender causes the RFID tag at the intended receiver, which is connected to the external interrupt pin of the micro-controller at that node, to generate an interrupt to wake up the MCU. The MCU wakes up and activates the radio voltage regulator and oscillator in preparation for the incoming packets. After a short start up time of few milliseconds for the radio components, the radio at the receiver becomes fully active. At this point, the sender commences the transmission. Once the sender completes all its packet transmissions, both sender and receiver again turn off their radios and MCU's.

Because certain RFID standards operate in the ISM band, which is the same band as the 802.15.4, an 802.15.4 radio, in addition to serving as a general-purpose communication radio [10], can potentially activate a remote passive RFID tag through an energy harvesting strategy (such as with a suitable comparator [9]), which in turn drives the activation

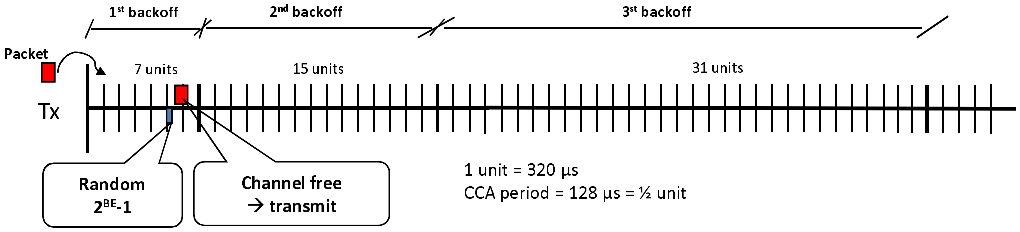

Fig. 1. Binary Exponential Backoff in IEEE 802.15.4

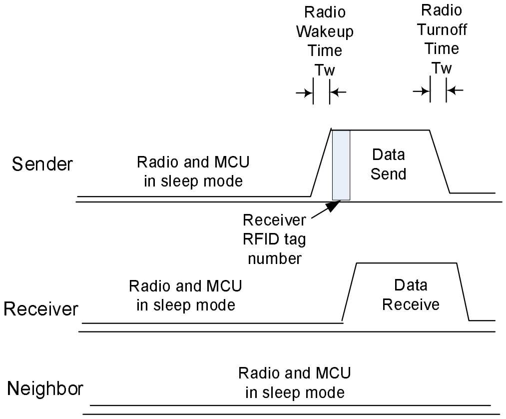

Fig. 2. High level timeline of RFIDImpulse

of the sensor node. Although RFIDImpulse is independent of the underlying MAC protocol, in the following discussion we describe how RFIDImpulse can enhance 802.15.4 MAC operation while maintaining compliancy with the standard.

The non-beacon enabled mode in 802.15.4 demands that nodes wake up periodically for a contention access period in order to avoid keeping the nodes awake all of the time. With RFIDImpulse, a node can put its radio and MCU in sleep mode as long as it has no data to send and as long as its RFID tag has not been triggered. A node typically has data to transmit either when it has just sampled its sensors, or when it has to receive a packet that requires forwarding. In the latter case, the node is already awake and can attempt to forward the packet immediately. If the node has a packet to send due to a sensing event, the sensor output can generate an external interrupt at the MCU, in addition to the RFID tag, which enables sensing events to trigger a wake up event of an MCU in deep sleep. Once the MCU is awake, it activates the radio. The radio then performs CCA, as in 802.15.4, in a random byte slot within the first 7 slots. In case the selected slot is busy, then the sender backs off, goes into idle mode, and then listens to the channel again in a random byte slot within the next 15 slots and so on.

As a receiver, the node sleeps until its RFID tag is triggered. The node MCU is then activated through an external interrupt generated by the tag, and then the MCU turns on the radio. The node then listens to the channel exactly as in 802.15.4. If it does not receive any packets destined for it during the first 7 time units, it stays awake for an additional 15 time units. If there is still no packets, the radio stays on for another 31 time units, at which point the node either has started receiving the packet, or can go back into sleep mode. The maximum listening duration during an awake interval is therefore 54 time units that corresponds to about 17 ms.

IEEE 802.15.4-compliant radios, such as CC2420, support three low power modes in addition to the active mode. The deepest sleep mode (M3) turns off the oscillator and voltage regulator, which minimizes radio energy consumption. Nodes that use M3 as a sleep mode must wait for about 2.4 ms every time they turn the radio back on, and the operation of switching the radio from mode M3 to active mode involve appreciable energy cost [13]. In contrast, the lightest sleep mode in the CC2420 (M1) provides much quicker switching back to active mode (30μs) and much cheaper switching energy cost. However, the energy consumption of a node while its radio is in M1 sleeping state is significantly higher than mode M3. This exposes an energy and delay tradeoff between how deep a node sleeps and how often it wakes up to send or receive packets. We mainly focus here on the energy tradeoff, leaving the details of delay-based selection of radio sleep mode as an open research direction for future work.

To address the energy tradeoff, RFIDImpulse supports traffic-based selection of low power radio modes, as a mechanism of managing energy and delay tradeoffs of putting the radio to sleep. When the traffic load is high in a particular region of the network, nodes use lighter sleep modes since they have to wake up frequently to send and receive packets. It is not worthwhile for nodes to go into deeper sleep modes because of the higher latency and switching energy involved in frequent wake up transitions. When the traffic load is low in a particular region of the network, switching between sleep and active states is less frequent, so nodes use deeper sleep modes that provide that highest energy savings for long term sleeping.

III. ANALYTICAL MODEL

In order to model the energy consumption of the three MAC protocols, this section considers all the energy components that contribute to the overall energy consumption at a node, including the micro-controller unit and radio activity. We consider a convergecast application where all nodes sample their sensor periodically and send the data towards the base station. In this application, the sensing activity is the same for all nodes and protocols, so we disregard this energy component for the protocol comparisons.

A. Microcontroller Unit Energy

The energy consumption at the micro-controller unit of sensor motes contributes significantly to energy consumption, yet this energy component is often disregarded when analyzing the energy consumption of sensor network communication protocols. While most protocols keep the MCU in standby mode when the node is idle, RFIDImpulse enables the MCU to go into power down mode and be awoken only through an external interrupt through the onboard RFID tag. As such, the MCU energy consumption while the node is idle:

$$E_{mcu}^{off} = T_{mcu}^{off} \times I_{mcu}^{off} \times V \tag{1}$$

where T_{mcu}^{off} is the total time during which the MCU is off, I_{mcu}^{off} is the current draw of the MCU while the node is idle, and V is the supply voltage. The value of I_{mcu}^{off} is the power down current I_{mcu}^{pd} for RFIDImpulse and the standby current I_{mcu}^{sb} for other protocols. The MCU energy consumption during active mode is:

$$E_{mcu}^{on} = T_{mcu}^{on} \times I_{mcu}^{on} \times V \tag{2}$$

where T_{mcu}^{on} is the total time during which the MCU is on, and I_{mcu}^{on} is the MCU current draw during normal operation mode. The total MCU energy consumption, then, is simply the sum of E_{mcu}^{off} and E_{mcu}^{on}.

B. Listening Energy

We define the listening energy consumption as the radio energy consumption when the radio is active but not receiving or sending any packets. Protocols that are based on low power listening, such as BMAC [4], have the following listening energy:

$$E_{listen}^{lpl} = \frac{S}{CK} \times T_{CH} \times I_{listen} \times V \tag{3}$$

where S is the sampling period, CK is the check interval, T_{CH} is the time during which the node remains awake every cycle, and I_{listen} is the current draw of the radio in listening mode.

In contrast, the listening energy in RFIDImpulse only depends on the number of packets to be sent or received, and not on the sampling period. A sender wakes up the intended receiver through the RFID tag, and then follows the 802.15.4 CCA and collision avoidance mechanism described in Section II-B. Considering the worst case in which the packet is sent, the sender performs CCA three times before finding a free slot. During all the other 51 time slots, the sender radio can go into idle mode, so the listening energy consumption per packet sent is:

$$E_{send} = (3 \times T_{CCA} \times I_{listen} + 51 \times T_{CCA} \times I_{\alpha} \times V) \tag{4}$$

where T_{CCA} is the CCA duration, α is the radio sleep mode in use that is equal to M1 for idle mode, and I_{α} is the current draw of the radio while idle. Whenever the receiver tag in RFIDImpulse activates the MCU, and then the radio, the radio must stay on while the sender is attempting to transmit, which in the worst case is 54 time units. Thus, the listening energy per packet received in RFIDImpulse is:

$$E_{recv} = 54 \times T_B \times I_{listen} \times V \tag{5}$$

Finally, the total node listening energy for RFIDImpulse can be expressed as:

$$E_{listen}^{rfid} = E_{send} \times P_{sent} + E_{recv} \times P_{recv} \tag{6}$$

where P_{sent} and P_{recv} are the number of packets sent and received at the node.

C. Switching Energy

The switching energy component [13] is the energy consumed for switching the radio state between states, including normal, power down, and idle modes. The following equation determines the energy consumed for switching the radio from sleep mode α to active mode:

$$E_{switch}^{\alpha} = \frac{(I_{active} - I_{\alpha}) \times T_{\alpha} \times V}{2} \tag{7}$$

where I_{active} is the current draw of the radio in active mode, I_{α} is the current draw of the radio in sleep mode α, and T_{α} is the time required for the radio to go from sleep mode α to active mode.

The switching energy consumption of duty cycling protocols relates to the length of the sampling period and the check interval. For a fixed check interval, the number of times that a node switches its radio on and off is proportional to the length of the channel sampling period. More specifically:

$$E_{switch}^{dut} = \frac{S}{CK} \times 2 \times E_{switch}^{\alpha} \tag{8}$$

The factor of 2 in the above equation accounts for switching back to mode α from active mode.

In RFIDImpulse, the switching energy does not depend on the sampling period, but it depends on the number of packets sent and received. As a receiver, a node switches from sleep mode to active mode whenever its tag is activated, and it stays awake for a maximum of 54 time units during the contention period. As a sender, a node switches from sleep to active mode to perform CCA. If the channel is busy, then the node goes into idle mode until the next back-off interval. This process may be repeated up to a maximum of 3 times. Thus, the total switching energy at a single node in RFIDImpulse is:

$$E_{switch}^{rfid} = 2 \times [P_{sent} \times (E_{switch}^{\alpha} + 3 \times E_{switch}^{idle}) + P_{recv} \times E_{switch}^{\alpha}] \tag{9}$$

D. Transmission Energy

The transmission energy component refers to the energy consumed for transmitting packets and their associated control overhead on the radio. During any time period, the transmission energy is expressed as:

$$E_t = P_{sent} \times P_{length} \times T_B \times I_t \times V \tag{10}$$

where P_{length} is the length of a packet in bytes, I_t is the current draw of the radio while in transmit mode, and T_B is the time for sending one byte over the radio.

E. Receiving Energy

The reception energy component refers to the energy consumed while receiving packets and their associated control overhead on the radio. During any time period, the reception energy is expressed as:

$$E_r = P_{recv} \times P_{length} \times T_B \times I_r \times V \tag{11}$$

where I_r is the current draw of the radio while in receive mode.

F. Sleeping Energy

The sleeping energy component is simply the energy consumption while the radio is in low power mode. The following equation computes the sleeping energy for a node that goes into sleep mode α when it is off:

$$E_{sleep} = T_{rf}^{off} \times I_\alpha \times V \tag{12}$$

The energy model described in this section provides the basis for evaluating energy performance and tradeoffs of the protocols and node platforms for varying traffic loads in the next section.

IV. PERFORMANCE EVALUATION

This section explores the inter-dependencies among MAC protocols, node platforms, and traffic load in sensor networks. In particular, we consider three MAC protocols: (1) the widely used BMAC protocol; (2) the standard IEEE 802.15.4 MAC protocol; and (3) RFIDImpulse. The performance evaluation here considers two widely used target platforms, namely the TelosB and the MicaZ platforms. TelosB uses an MSP 430 processor and a CC2420 radio [3], while MicaZ uses the same radio with an Atmel128 [2] processor.

The first part of this section exposes the energy tradeoffs of the three MAC protocols for a low sampling rate multi-hop scenario and a high sampling rate multi-hop scenario. We obtain results for each of the target node platforms separately. The goal of these simulations is to expose the dominant energy components for each protocol on the basis of traffic load and node platform. Building on these results, the second part of this section determines the energy consumption of each MAC protocol based on traffic load, and identifies the best performing protocol for each node platform and traffic load.

Table I summarizes all the simulation parameters, while distinguishing between common simulation parameters for all protocols, parameters for duty cycling protocols that include BMAC and 802.15.4, and parameters that are specific to each protocol. All of the parameters relating to the CC2420 radio are based on measurements we have conducted with an oscilloscope to determine the current draw and transition latency for each power mode. All of the MCU-specific parameters have been obtained from the respective data sheets of the MSP430 datasheet for the TelosB platform and the ATMEL128 platform for the MicaZ platform. We now highlight the main differences in the simulation parameters for the protocols.

Protocol	Parameter	Value	Units
All	Supply Voltage (V)	3	V
	Active Atmel MCU current (I_{mcu}^{on})	12	mA
	Active MSP MCU current (I_{mcu}^{on})	0.35	mA
	Listening Mode Current (I_{listen})	18.8	mA
	Transmit Mode Current (I_t)	17.4	mA
	Receive Mode Current (I_r)	19.7	mA
	Clear Channel Assessment ((T_{CCA})	128	μSec
	Sleep Current (I^α) α=M3	0.2	mA
	Active Radio Current I_{active}	19.7	mA
	Byte Transmission Time (T_B)	32	μSec
Duty Cycling	Inactive Atmel MCU Current (I_{mcu}^{off})	4.1	mA
	Inactive MSP MCU Current (I_{mcu}^{off})	75	μA
RFIDImpulse	Inactive Atmel MCU Current (I_{mcu}^{off})	0.25	mA
	Inactive MSP MCU Current (I_{mcu}^{off})	6	μA
	Sleep Current (I^α) α=M1	1	mA
	Sleep Current (I^α) α=M2	0.5	mA
	Active Radio Current I_{active}	19.7	mA
	Idle Switching Energy (E_{switch}^{idle})	827	nJ
BMAC	Check Interval (CK)	10	mSec
	Check Time (T_{CH})	128	μSec
IEEE 802.15.4	Check Interval (CK)	50	mSec
	Check Time (T_{CH})	17.28	mSec

TABLE I
SIMULATION PARAMETERS

RFIDImpulse enables a node to put both its radio and microprocessor in the deepest sleep mode (M3) when the node has no communication activity. Nodes can be awoken by an external interrupt from the RFID tag attached to the MCU. Nodes can also put their radio in idle mode (M1) or medium sleep mode (M2) based on traffic activity in the network. Nodes always use idle mode during the contention period when they are about to send or receive a packet. In contrast, both BMAC and 802.15.4 require that the MCU remains in standby mode when the radio is asleep with a low speed oscillator running, in order to maintain system timers and scheduled interrupts.

With regards to check interval, we set this parameter to 10ms for BMAC to accommodate high traffic scenarios, as recommended in [4]. During each check interval, the radio only stays active for a CCA period, and goes back into mode M3 if no activity is detected on the channel. For 802.15.4, the radio must stay awake for up to 54 time units or 17.28 ms every check interval, so we set the check interval to 50 ms for 2 reasons: (1) to keep in line with BMAC listening modes that provide a check interval of 10, 20, 50, 100, 200, 400, 800, or 1600 ms; and (2) to ensure that the node can sleep for a worthwhile period of time prior to waking up for another contention period. The data payload size in all simulations is 100 bytes, while the preamble length are as follows: 4 bytes for RFIDImpulse to send the RFID address; 364 bytes for the long preamble in BMAC to match the 10 ms check interval; and 16 bytes for the 802.15.4 non-beacon enabled mode header.

Finally, note the lower current draw for MSP430 relative ATMEL128 processors for active, idle and power down modes. The reduced MSP430 current draw results in lower MCU power consumption, reducing the impact of E_{mcu} on protocol performance with this platform.

A. Energy Tradeoffs

We first explore the energy tradeoffs of the three protocols mentioned above. In this evaluation, we consider a network

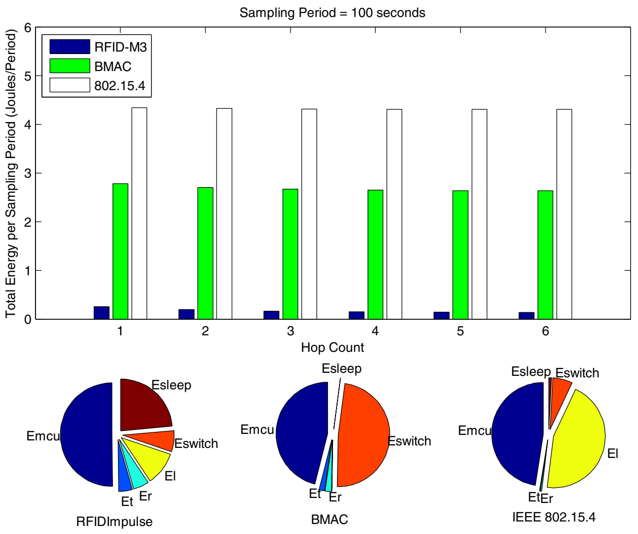

Fig. 3. Power consumption tradeoffs for MicaZ at a sampling period of 100 seconds

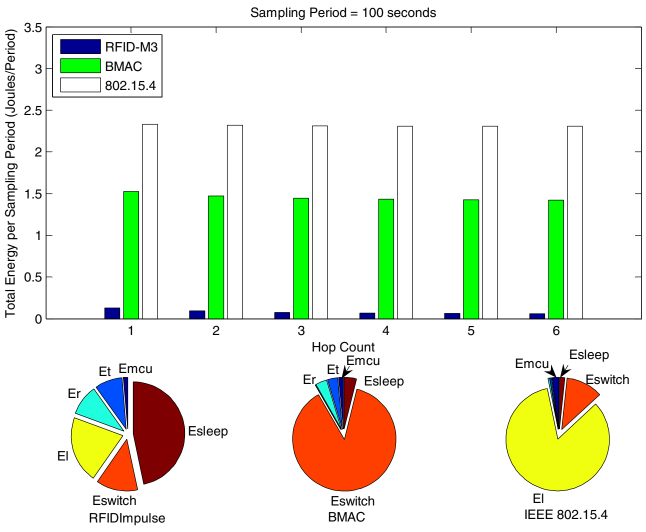

Fig. 4. Power consumption tradeoffs for TelosB at a sampling period of 100 seconds

with a 6-hop binary tree static topology. Although the topology of an actual sensor network can be both irregular and transient according to environmental conditions as well as location, this study serves as a representative case that exposes the energy tradeoffs of the three MAC protocols for the MicaZ and TelosB platforms under varying traffic loads. The network is convergecast in nature where all nodes periodically sample their sensors and send the data in a packet towards the base station that is co-located with the root of the tree topology. Packets are forwarded in a multi-hop fashion until they reach the base station. Each node's hop count from the root in the logical topology determines its forwarding load. Intermediate nodes must forward all packets of their children, while leaf nodes only send their own packets.

The first scenario considers the energy tradeoffs in a six hop binary tree network with a low data rate, in which the sampling period S is set to 100 seconds. Because of the low traffic load in this scenario, RFIDImpulse uses the deepest sleep mode M3. Figure 3 shows the energy tradeoffs corresponding to RFIDImpulse-M3, BMAC and 802.15.4 for the MicaZ platform. The bar graph in Figure 3 illustrates the energy consumption of nodes at each level within the tree network for each of the three protocols. In this scenario, the overall energy consumption of RFIDImpulse-M3 is about 20 times lower than for 802.15.4 and about 13 times lower than BMAC at all levels of the topology. Both BMAC and 802.15.4 require the nodes to wake up periodically to check the channel for activity proactively, whereas RFIDImpulse operates in an on-demand fashion and wakes up nodes only when there is data to send or receive. The frequent switching on and off of radios causes higher energy consumption for both BMAC and 802.15.4. The latter has the highest energy consumption because every time a node wakes up, it has to stay awake in listening mode for up to 17 ms, causing high idle listening energy consumption. Finally, BMAC and 802.15.4 keep the MCU in standby mode all the time because of the need to maintain timers, which contributes further to their higher energy consumption. RFIDImpulse, on the other hand, enables the MCU to go into power down mode and to wake up through an external interrupt generated with the attached RFID tag.

The results also show that the energy consumption of all three protocols does not have a significant dependance on the node's hop count from the base station. To explain this trend, we refer to the three pie charts in the lower part of Figure 3 that break down the energy consumption of nodes at hop count 1 (the critical nodes) for each protocol.

For all three protocols, the energy consumption of the MCU represents a major portion of overall energy consumption. In RFIDImpulse, E_{mcu} is high because the MCU is awake more often the radio, both during the back-off period and whenever the RFID tag is triggered and the radio is in transition between states. In both BMAC and 802.15.4, the MCU is always in standby mode when the radio is in mode M3, which causes E_{mcu} to be relatively high. Notably, the switching energy component, which is often disregarded in MAC protocol evaluations, accounts for about half of the overall energy consumption for BMAC. The high switching energy for BMAC is due to the 10ms check interval which causes the node to switch between active and sleep mode 10,000 times during the 100 second sampling period. In 802.15.4, E_l accounts for almost half the overall energy consumption, as nodes must stay awake for up to 54 T_B every time they wake up, in contrast to the T_{CCA} of BMAC.

Figure 4 shows the energy consumption tradeoff for the same sampling period of 100 seconds with the TelosB platform. The energy consumption trend among the three protocols and among the tree levels are similar to results for MicaZ. However, the energy consumption is about 40% lower for TelosB than MicaZ, mainly due to the reduced energy consumption of the MSP430 MCU for TelosB relative to the Atmel128 MCU used in MicaZ. The pie charts in the lower part of Figure 4 confirm that the MCU accounts for a much smaller slice for TelosB for all MAC protocols, whereas the MCU was dominant for all protocols with MicaZ.

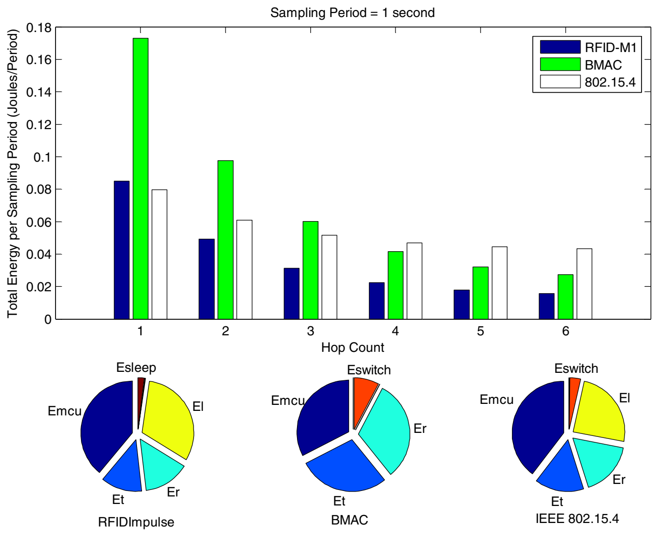

Fig. 5. Power consumption tradeoffs for MicaZ at a sampling period of 1 second

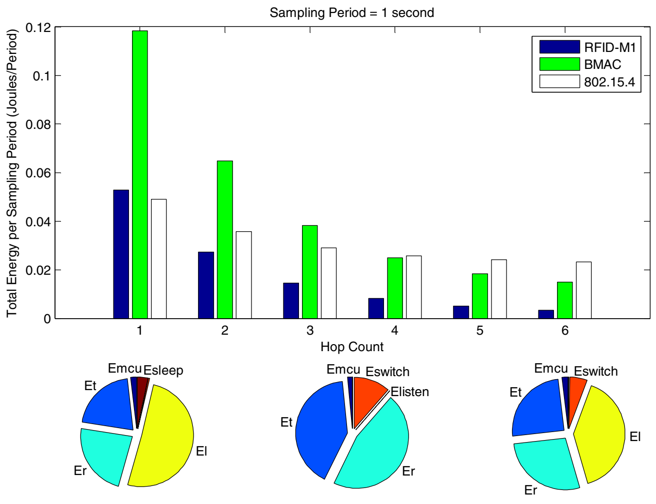

Fig. 6. Power consumption tradeoffs for TelosB at a sampling period of 1 second

With the shrinkage of MCU energy consumption, other energy components become more prominent for TelosB. For RFIDImpulse, the sleeping energy now dominates energy consumption, accounting for about half of the overall energy consumption since nodes have their radio in sleep mode for most of the time. The switching energy component also appears as a significant contributor to overall energy consumption, as nodes switch back and forth between sleep and active mode for every packet transmission. Every time nodes switch on their radios, the collision avoidance mechanism of 802.15.4 kicks in, which explains the sizeable contribution of E_l for RFIDImpulse.

The reduced significance of MCU energy consumption for TelosB has even greater impact on energy consumption contributors for BMAC and 802.15.4. For BMAC, the switching energy accounts for more than 85% of overall energy consumption with TelosB, because of the need to wake up the radio for every CCA in low power listening. For 802.15.4, the listening energy accounts for more than 80% of overall energy consumption with TelosB, due the collision avoidance algorithm in the non-beacon enabled mode.

The second scenario considers the energy tradeoffs in a six hop binary tree network with a high data rate, in which the sampling period S is set to 1 seconds. Because of the high traffic load in this scenario, RFIDImpulse uses the lightest sleep mode M1. Figure 5 shows the energy tradeoffs corresponding to RFIDImpulse-M1, BMAC and 802.15.4 for the MicaZ platform. The energy consumption for all protocols in this high traffic scenario increases progressively for nodes closer to the base station, because the higher traffic load at these nodes increases the significance of energy consumption associated with packet forwarding. For nodes closer to the leaf level (nodes with hop count 4-6), BMAC outperforms 802.15.4 because these nodes have a small forwarding load. Nodes at hop count 1-3 save more energy with 802.15.4 than with BMAC, because 802.15.4 uses shorter packet preambles than BMAC. RFIDImpulse exhibits the lowest energy consumption for all levels in the tree except level 1, where nodes consume more higher energy than 802.15.4.

Referring to the energy component breakdown in the pie charts of Figure 5, E_{mcu} remains a major contributor to overall energy consumption with MicaZ with all protocols. Compared to the low traffic scenario, the MicaZ with RFIDImpulse exhibits higher energy contributions from radio listening energy, due to frequent collision avoidance listening, and from receiving and sending energies, due to increased traffic. In contrast, Switching and sleeping energy components shrink in importance. In fact, the sending and receiving energy components gain prominence for all protocols in the high traffic case, simply as a consequence of increased number of packets to be sent and received. We also note the negligible E_{switch} component for RFIDImpulse, since the M1 mode involves low energy cost for switching between states.

We now consider the same high sampling rate scenario for TelosB. Figure 6 shows the energy consumption of the three protocols and the energy component breakdown. As in the low sampling rate scenario, TelosB exhibits the same trend among the three protocols as MicaZ, with about a 40% decrease in energy consumption. The trend between nodes at different hop counts are also similar to MicaZ, but we note the lower relative energy consumption of nodes at hop counts 3-6 for RFIDImpulse. This effect stems from the increased contribution of E_t and E_r and the decreased contribution of E_{mcu}, which causes nodes with more forwarding traffic to have higher energy consumption.

In the energy breakdown results, E_r and E_t certainly gain prominence for all protocols, as in the case of MicaZ. For RFIDImpulse, E_l accounts for about half of the overall energy consumption, as E_{mcu} shrinks for TelosB. For BMAC, the switching energy becomes appreciable, but less so than for the low traffic case of TelosB, as the dominant energy components for the high traffic case are E_r and E_t. Finally, 802.15.4 exhibits a similar breakdown of energy components as RFIDImpulse for TelosB, with the exception of the higher switching energy for 802.15.4, because it uses sleep mode M3 whereas RFIDImpulse uses sleep mode M1.

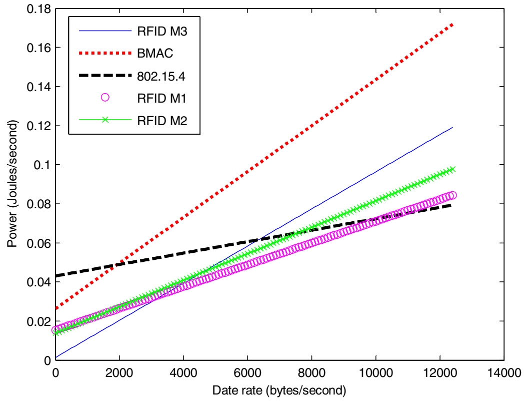

Fig. 7. Power consumption as a function of data rate for MicaZ

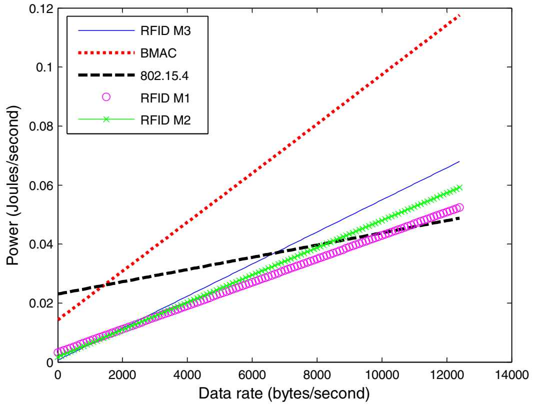

Fig. 8. Power consumption as a function of data rate for TelosB

The results in this section have shown so far that TelosB can save up to 40% in energy consumption over MicaZ. The results have also indicated that RFIDImpulse is more energy-efficient than BMAC in low traffic scenarios, and that 802.15.4 and RFIDImpulse have comparable energy performance in high traffic scenarios, thanks to the latter's exploitation of traffic-based radio low power modes. The next subsection determines the best protocol/power mode to use for varying data rates with each of the node platforms.

B. Optimal Traffic Load

This section uses the term data rate to express the total useful data rate, excluding all headers, footers, and preambles. We make this designation in order to compare the three protocols, which have different packet formats and preamble lengths, along the same axis. However, the energy consumption does take into account all communication overhead as well as useful data payloads.

We consider a data rate between 0 bytes/second, for nodes that have no data to send or receive, and 12,500 bytes, which corresponds to the maximum useful data rate at a level 1 node in the tree topology network in section IV-A. We determine the energy consumption of all protocols at each data rate through the model in section III. For RFIDImpulse, we determine the energy consumption at each data rate for each of the three possible sleep modes M1, M2, and M3.

Figure 7 plots the power consumption of the protocols as a function of data rate for the MicaZ platform. For data rates below 3500 Bytes/second, RFIDImpulse-M3 has the lowest energy consumption. For data rates between 3500 and 10500 bytes, RFIDImpulse-M1 exhibits the best energy performance. For high data rates, 802.15.4 has the lowest energy consumption. These results serve as the basis for adaptive low power mode/protocol selection in software. As RFIDImpulse builds on 802.15.4 radios, switching between M1, M3, and basic 802.15.4 operation can be simply implemented as a cross-layer mechanism that monitors communication traffic and decides the optimal mode through the analytical model in section III. As for BMAC, it outperforms 802.15.4 for low data rates up to 1900 bytes/second, at which point 802.15.4 performs better.

Figure 8 plots the power consumption of the protocols as function of data rate for the TelosB platform. Although the energy consumption trends are similar to MicaZ, we note that RFIDImpulse-M3 has the lowest energy consumption only for data rates up to 1300 bytes/second. Another notable difference is that RFIDImpulse-M2 is the best performing protocol for data rates between 1300 and 2200 bytes/second, whereas this mode is not optimal for any data with MicaZ. For data rates between 2200 and 10400 bytes/second, RFIDImpulse-M1 has the lowest energy consumption, and 802.15.4 is the best performing protocol for high data traffic.

Figures 9 and 10 summarize the recommended operation mode/protocol for the MicaZ platform and the TelosB platform respectively, on the basis of data rate. For both platforms, RFIDImpulse-M3 is recommended for low traffic scenarios, since it yields the largest energy savings in sleep mode. For very high data traffic, the recommendation is using 802.15.4, as the switching and backoff listening energy in RFIDImpulse grow for higher traffic. For medium traffic scenarios, the results indicate that RFIDImpulse-M1 performs best. The exception to this rule is for data rates between 1300 and 2200 bytes, where RFIDImpulse-M2 has the lowest energy consumption. Another notable difference for the two platform is that the threshold data rates for switching modes are lower for TelosB relative to MicaZ. In other words, Figure 9 recommends switching to RFIDImpulse-M1 for a data rate of 3500 bytes/second with MicaZ, whereas we would switch to M1 at 2200 bytes/second with TelosB. This difference stems from the reduced significance of E_{mcu} for TelosB, which places a higher dependence of energy consumption on data rate, in the form of E_r and E_t.

Because RFIDImpulse is still in the implementation process, Figures 9 and 10 also provide a head-to-head comparison between the widely used protocols BMAC and 802.15.4. For MicaZ, BMAC has lower energy consumption than 802.15.4 for data rates up to 1900 bytes/second, and 802.15.4 performs better for all higher data rates. For TelosB, BMAC performs better than 802.15.4 up to 1400 bytes/second. The recommendation of this head-to-head comparison is then to consider the data traffic requirements for a particular sensor network application and the target node platform. If the data rate requirements for the application are lower than the critical threshold (1900 bytes/second for MicaZ, 1400 bytes/second for TelosB), then BMAC should be used. Otherwise, the

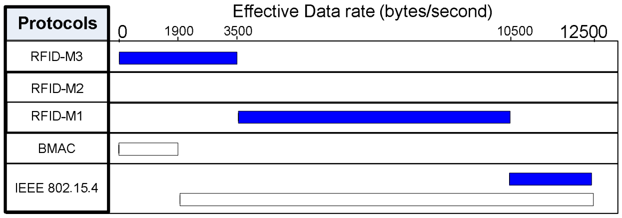

Fig. 9. MicaZ recommended operation modes

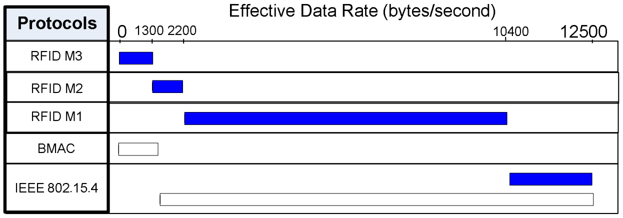

Fig. 10. TelosB recommended operation modes

application should use 802.15.4.

V. DISCUSSION

This paper has provided an analytical model to conduct a comparative analysis study of MAC protocol suitability of BMAC, IEEE 802.15.4, and the newly proposed RFIDImpulse across two popular node platforms, MicaZ and TelosB. The study has used *measured values* for CC2420 radio current draw in each of its operation modes for a realistic comparison of the protocols.

Building on the dependence of protocol performance on traffic loads, the paper has also introduced the concept of adaptive low power radio sleep modes based on the level of data traffic in the network. As a rule of thumb, deeper sleep modes should be used for low data traffic scenarios because they have the lowest energy consumption for long sleep duration, and lighter sleep modes should be used for high traffic scenarios because they provide the quicker and less costly switching energy for frequent transitions between sleep and active modes. The results in Figures 7 and 8 specify the quantitative relationship between optimal radio sleep modes and data rates.

The comparative protocol performance analysis has shown that RFIDImpulse-M3 has the lowest energy consumption for low traffic scenarios for both two node platforms. Medium data traffic demands a switch to RFIDImpulse-M1 to maintain minimal energy consumption, whereas 802.15.4 performs best for high data traffic. In a head-to-head comparison between BMAC and 802.15.4, BMAC performs better for low data rates, while 802.15.4 performs better for higher data rates.

These results lay the groundwork for an enhanced IEEE 802.15.4-compliant MAC protocol that adapts the radio low power sleep mode in use according to observed data traffic. Sleep mode adaptation can be done on a network-wide or per-node basis through the analytical model in Section III. In a network-wide implementation of such a protocol, the base station monitors traffic flow, determines the optimal low power mode for the busiest node in the network, and broadcasts this mode to all network nodes. A per-node implementation demands that each node runs the model periodically and determines its own optimal low power mode based on its traffic load, but it also requires that nodes piggyback their current low power mode in use unto periodic beacon messages so that all neighbors are aware of low power modes in use in their neighborhood [5]. In both implementations, a sender that is aware of the low power mode in use at the receiver can send a wake-up message and wait an appropriate length of time to allow the receiver to power up its sleeping radio components before commencing data transmission.

The results have also highlighted the reduction of MCU energy consumption by TelosB over MicaZ, which yields about 40% overall energy savings for networks that use TelosB. The reduction of MCU energy consumption in TelosB also gives prominence to the transmission and reception energy for this platform, rendering protocol performance more sensitive to the data traffic changes, as Figures 9 and 10 confirm. Note that the results here are also applicable to most sensor node platforms that use ATMEL128 or MSP430 in combination with the CC2420 radio.

Cross-layer dependencies in sensor networks [15] require consideration of not only energy performance based on the choice of hardware and MAC protocols, but also the delay performance and the choice of routing and scheduling protocols as well. An interesting direction for future work is to explore the inter-dependencies and between the choice of node platforms, MAC protocols, and routing and scheduling protocols. Keeping in mind that these dependencies exist, the measurement-based comparative study in this paper will hopefully serve as a guide for sensor network researchers in selecting node platforms and MAC protocols that are suitable for the expected traffic requirements in their applications.

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