Multi-hop RFID Wake-up Radio: Design, Evaluation and Energy Tradeoffs

Raja Jurdak, Antonio G. Ruzzelli, Gregory M. P. O'Hare

School of Computer Science and Informatics,
University College Dublin
{raja.jurdak, ruzzelli, gregory.ohare} @ucd.ie

***Abstract*—Energy efficiency is a central challenge in battery-operated sensor networks. Current energy-efficient mechanisms employ either duty cycling, which reduces idle listening but does not eliminate it, or low power wake-up radio, which adds complexity and cost to the sensor platform. In this paper, we propose a novel mechanism called RFIDImpulse that uses RFID technology as an out-of-band wake-up channel for sensor networks. RFIDImpulse is an on-demand mechanism that enables nodes to sleep until they have to send or receive packets. It relies on IEEE 802.15.4 radio to emulate an RFID reader at a sender node, and on an off-the-shelf RFID tag attached to the external interrupt pin of each sensor node. The sender can simply activate the receiver's tag before sending it data packets. This setup enables both radio and microcontroller to go into deep sleep mode until they need to be active. We develop an analytical model to evaluate the energy tradeoffs of RFIDImpulse, and then evaluate the mechanism against BMAC and IEEE 802.15.4 in high and low traffic scenarios. The results confirm that RFIDImpulse reduces the energy consumption relative to both protocols for low and medium traffic scenarios, and they reveal the thresholds for adaptive activation of RFIDImpulse based on traffic load.**

I. INTRODUCTION

Recent advances in wireless communication, processing capability, and memory technology have fueled increasing research and industrial activity around wireless sensor networks (WSN). Wireless sensor technology involves battery-operated wireless modules equipped with one or more sensors that capture data from a physical space and make it available in the digital domain.

Sensor nodes typically have limited form factor, which demands the use of small batteries. This requirement has highlighted energy consumption as a primary issue in WSN's, as battery replacement is costly and often difficult in inaccessible deployment regions. Several efforts have addressed the energy efficiency, and these can be classified into two main categories: (1) duty cycling; (2) wake-up radio.

Duty cycling protocol are based on the premise that idle listening is the dominant cause of energy consumption, so they put sensor nodes into sleep mode and enable them to wake up periodically to check the channel for activity [4, 6]. In case the node detects an imminent packet transmission intended for it, it stays awake to receive the packet. Otherwise, it continues the duty cycling process. By allowing the nodes to sleep for the majority of time, duty cycling protocols reduce idle listening in WSN's. Duty cycle protocols are proactive in nature, so even if no data packets are present, nodes continue to switch their radios from active to sleep mode periodically. This represents a major drawback in duty cycling protocols.

Wake-up radio protocols employ an out-of-band low power radio for signalling an upcoming packet transmission. Nodes can remain asleep until they receive a signal on the wake up radio, at which point they activate their radio and begin receiving data. Unlike duty cycling protocols, wake-up radio protocols are on-demand as nodes are only awoken when they are the intended senders or receivers of data packets. As such, wake-up radio protocols exhibit higher reductions in the idle listening energy consumption. However, wake-up radio typically comes with increased hardware complexity and module cost for including a second radio.

Using RFID as the wake-up radio channel provides a viable solution as RFID tags are both cheap and readily available off-the-shelf. Although this solution has been proposed in [17, 18], the performance implications of using RFID as an out-of-band wake up radio in multi-hop WSN's have remained largely unexplored. In this paper, we present the design, evaluation and performance tradeoffs of an RFID wake up mechanism for wireless sensor networks, called RFIDImpulse, that we had proposed in [18]. Nodes using RFIDImpulse can put both their radios and microprocessor units (MCU) into the deepest sleep modes available. It uses an RFID tag reader at a sending node to trigger an RFID tag that is connected to the external interrupt pin of the MCU at the intended receiver. The RFID reader can activate a single remote tag by including the remote tag's unique ID in the signal. Once triggered, the receiver tag generates an interrupt to the MCU causing it to wake up and in turn to activate the radio for data reception. This mechanism can also exploit the common ISM 2.4 GHz spectrum between IEEE 802.15.4 [20] and RFID to use the sensor radio at the sender to emulate an RFID tag reader and to trigger the remote tag, which eliminates the need for a separate RFID tag reader at each node.

The main features of RFIDImpulse are the following:

- On-demand communication: Communication is asynchronous and reactive to data patterns, as nodes only wake up to send or receive data.
- MAC-protocol independent: RFIDImpulse can operate in conjunction with any underlying MAC protocol.
- Accommodates MAC features: Being protocol-

independent, RFIDImpulse can exploit collision avoidance mechanisms, such as binary exponential back-off, available at the MAC.
- Minimizes idle listening: Because nodes in RFIDImpulse only activate their radio when there are packets to send or receive, RFIDImpulse reduces idle listening relative to duty cycling protocols.
- Low transmission overhead: Whereas duty cycling protocols incur control overhead in the form of periodic synchronization messages [4] or long preambles [6], RFIDImpulse only has minimal overhead in the form of the RFID tag address.

While our earlier work in [18] had introduced the node configuration and basic operation of RFIDImpulse, this paper focuses on exploring through simulations the energy tradeoffs of RFIDImpulse relative to BMAC, the most widely used duty cycling MAC protocol in sensor networks, and the IEEE 802.15.4 MAC, which is the official MAC standard for WSN's.

The remainder of the paper is organized as follows. Section II discusses related work on existing MAC protocols and radio-triggered techniques. Section III presents the details of the RFIDImpulse operation, while Section IV provides the analytical model for evaluating the energy benefits of this mechanism. Section V compares the performance of RFIDImpulse relative to the two representative existing protocols, and section VI discusses the results and concludes the paper.

II. RELATED WORK

Common energy-efficient communication protocols used for wireless sensor networks such as [4, 6–9] are based on duty -cycling the activity of nodes. Some duty cycling approaches result in idle listening at the receiver such as SMAC [4]. Alternative duty cycling approaches shift the idle listening energy overhead to transmitter, such as in BMAC [6] or in MERLIN [9], in order to save energy in low data rate scenarios. Current duty cycle protocols can only reduce but not eliminate idle listening, which remains the main source of power dissipation in sensor networks. In the pursuit of mechanisms that would greatly reduce the node duty cycle and allow fast channel assessment, the authors in [14] proposed a support from a special hardware transceiver that can reduce time needed for a radio to perform clear channel assessment. By introducing extra hardware, the mechanism can mitigate further the idle listening but it does not eliminate it. Furthermore, such time slotted communication approaches such as [4, 9, 10] must rely on a tight time synchronization procedure, for example [11], with an increase in transmission overhead. Although these drawbacks can be resolved by allowing remote wake-up, this field is relatively new and it has not been fully investigated.

An alternative approach is to use a low-power wake up radio component such as PicoRadio [13] to watch the channel when the node enters the sleep mode. The drawbacks of PicoRadio is that it uses extra node energy to power up a separate low-power radio to monitor the channel activity and to wake-up the main radio transceiver in case the node senses channel activity destined for it.

An RFID wake-up scheme similar to RFIDimpulse has been previously presented in a poster in [17]. However, the authors only provide a high level description without providing any details about how the methodology can be implemented and the communication implications for access control and routing in a multihop network.

To our knowledge, the most relevant contribution to RFIDImpulse on remote wake-up mechanisms is the remote radio-triggered sensors in [12]. The work in [12] proposes different circuits that can be remotely triggered by the transmitter. The proposed circuits wake-up the node if a packet at a particular frequency is received. In this approach, a node can wake up the entire neighborhood simultaneously. Alternatively, it employs multiple transceivers to transmit radio signals at different frequencies simultaneously so that a transmitting node can select a receiver. This is not always available in off-the-shelf sensor modules. Furthermore, the approach presents a limited operating distance of about 7m. In contrast, our approach uses ISO standard RFID protocols such as ISO18xxx, that use one channel to enable all neighbouring nodes to receive the impulse and wake up simultaneously or the RFID reader can select which neighboring node to trigger, and it has a range of 10m for passive RFID tags and 50-70m for semi-passive RFID tags.

III. RFIDIMPULSE

This section presents the RFIDImpulse mechanism. 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 as follows. 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 microcontroller 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 to the receiver. Once the sender completes all its packet transmissions, both the 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 IEEE 802.15.4, an IEEE 802.15.4 radio can potentially serve the dual purpose as an RFID reader and general-purpose radio [15]. Although RFIDImpulse is independent of the underlying MAC protocol, in the following discussion we describe how RFIDImpulse can enhance IEEE 802.15.4 MAC operation while maintaining compliancy with the standard. The next subsection provides an overview of the IEEE 802.15.4 MAC protocol functionality.

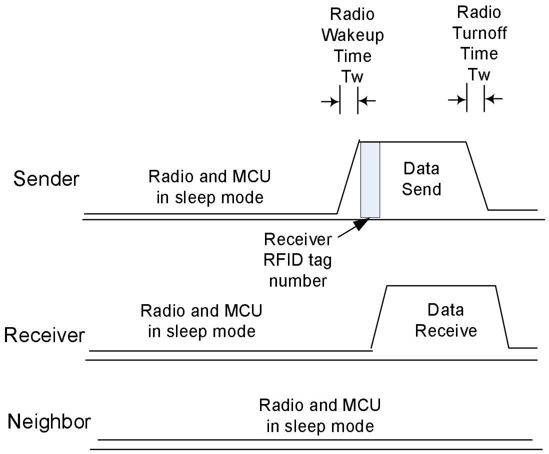

Fig. 1. High level timeline of RFIDImpulse

Next, we discuss how RFID impulse can operate alongside the IEEE 802.15.4 MAC to enable nodes to go into deep sleep modes when idle, significantly reducing idle listening.

A. *Overview of IEEE 802.15.4*

The IEEE 802.15.4 standard [20] 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. As RFIDImpulse operates asynchronously in an on-demand fashion, we focus here on the non-beacon enabled mode. In non-beacon enabled-enabled mode, no beacons are broadcast, so IEEE 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 2 shows the backoff structure of IEEE 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 reschedules its packet for a later time.

B. *RFIDImpulse over IEEE 802.15.4*

The RFIDImpulse mechanism is compatible with almost any underlying MAC protocol, including IEEE 802.15.4-enabled radios, with no modifications required to the standard. Currently, the non-beacon enabled-enabled mode in IEEE 802.15.4 demands that node 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 deep 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 goes into Contention Access mode, just as in IEEE 802.15.4, and performs CCA in a random byte slot with 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 IEEE 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 a CAP is therefore 54 time units that corresponds to about 17 ms.

IV. ANALYTICAL MODEL

In order to model the energy consumption of RFIDImpulse against other protocols, this section considers all the energy components that contribute to the overall energy consumption at a node, including the microcontroller 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 microcontroller unit of sensor nodes 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

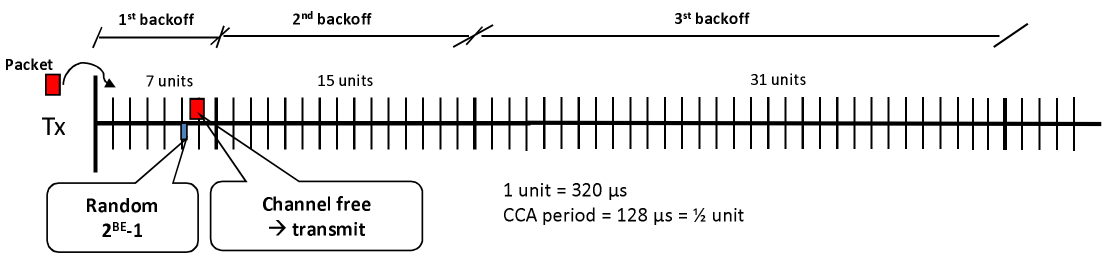

Fig. 2. Binary Exponential Backoff in IEEE 802.15.4

I^{sb}_{mcu} for other protocols. The MCU energy consumption during active mode is:

$$E^{on}_{mcu} = T^{on}_{mcu} \times I^{on}_{mcu} \times V \tag{2}$$

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

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 [6], have the following listening energy:

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

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 S. A sender wakes up the intended receiver through the RFID tag, and then follows the IEEE 802.15.4 CCA and collision avoidance mechanism described in Section III-A. 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 sender energy consumption per packet is:

$$E_{send} = (3 \times T_{CCA} \times I_{listen} + 51 \times T_{CCA} \times I^{id}_{rf}) \times V \tag{4}$$

where T_{CCA} is the CCA duration, and I^{id}_{rf} 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 receiving energy per packet 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:

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

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

C. Switching Energy

The switching energy component [19] 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:

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

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 S and CK. For a fixed CK, the number of times that a node switches its radio on and off is proportional to the length of CK. More specifically:

$$E^{dut}_{switch} = \frac{S}{check} \times 2 \times E^{\alpha}_{switch} \tag{8}$$

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

In RFIDImpulse, the switching energy does not depend on S, 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:

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

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:

$$E_r = P_{recv} \times P_{length} \times T_B \times I_r \times V \qquad (11)$$

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:

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

The energy model described in this section provide the basis for evaluating energy performance and tradeoffs of RFIDImpulse against existing protocols in the next section.

V. PERFORMANCE EVALUATION

This section compares the performance of RFIDImpulse relative to two widely used MAC protocols, BMAC and IEEE 802.15.4, through Matlab simulations that integrate the analytical model of Section IV. The first part of this section exposes the energy tradeoffs of the three protocols for a low sampling rate multi-hop scenario and a high sampling rate multi-hop scenario. The second part of this section evaluates the effect of forwarding load for each protocol in a multi-hop scenario and identifies the optimal operating region of RFIDImpulse.

The target platform for our simulations is the MicaZ from Crossbow, which has a CC2420 radio [3] and an ATMEL128 microprocessor [2]. 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 IEEE 802.15.4, and parameters that are specific to each protocol. All of the parameters have been obtained from the respective data sheets of CC2420 and Atmega128. We now highlight the main differences in the simulation parameters for the protocols.

RFIDImpulse enables a node to put both its radio and microprocessor in the deepest sleep mode when the node has no communication activity. Nodes can be awoken by an external interrupt from the RFID tag attached to the MCU. Nodes go into idle mode only during the contention period when they are about to send or receive a packet. In contrast, both BMAC and IEEE 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 CK, we set this parameter to 10ms for BMAC to accommodate high traffic scenarios. During each check interval, the radio only stays active for a CCA period, and goes back into idle mode if no activity is detected on the channel. For IEEE 802.15.4, the radio must stay awake for up to 54 time units or 17.28 ms every check interval, so we set CK 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. Because the node must keep its radio on for 17.28ms every time it turns on its radio, then a check interval of 20ms would only allow the node to turn its radio on for less than 3 seconds before having to turn it back on. For these reasons, the check interval for IEEE 802.15.4 is set to 50ms in our simulations.

Protocol	**Parameter**	**Value**	**Units**
All	Supply Voltage (V)	3	V
	Active MCU current (I_{mcu}^{on})	12	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^{alpha})	1	μA
	Active Radio Current I_{active}	19.7	mA
	Byte Transmission Time (T_B)	32	μSec
Duty Cycling	Inactive MCU Current (I_{mcu}^{off})	4.1	mA
RFIDImpulse	Inactive MCU Current (I_{mcu}^{off})	0.25	mA
	Idle Radio Current (I_{rf}^{id})	0.426	mA
	Idle Switching Energy (E_{switch}^{idle})	827	nJ
	MCU power down current (I_{mcu}^{off})	0.25	mA
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

A. *Energy Tradeoffs*

We first explore the energy tradeoffs of the three protocols mentioned above. In this evaluation, we consider a network 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 RFIDImpulse relative to BMAC and IEEE 802.15.4. 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.

Figure 3 shows the energy tradeoffs of the three protocols in the six hop binary tree topology network for a low data rate scenario, in which S is set to 100 seconds. In this scenario, the overall energy consumption of RFIDImpulse is about 20 times lower than for IEEE 802.15.4 and about 13 times lower than BMAC. The results show that the energy benefits of all three protocols do not have a significant dependance on the

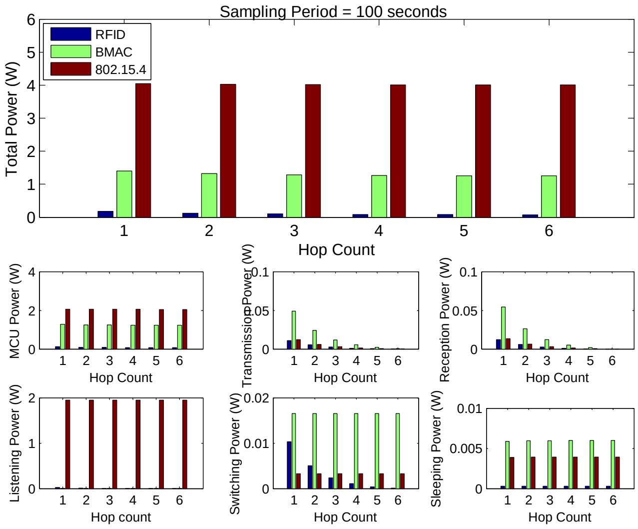

Fig. 3. Power consumption tradeoffs for a sampling period of 100 seconds

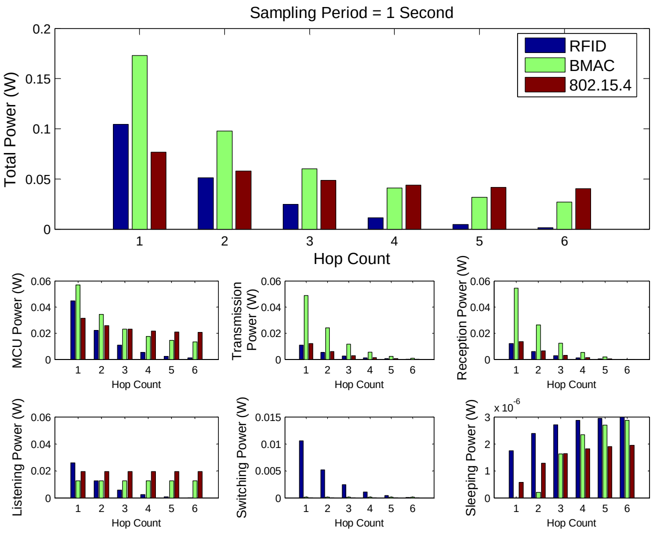

Fig. 4. Power consumption tradeoffs for a sampling period of 1 seconds

node's hop count from the base station. The subsequent figures expose the factors that drive the energy consumption for each protocol.

The listening and MCU energy components are dominant in their contribution to the overall energy consumption of BMAC and IEEE 802.15.4. In IEEE 802.15.4, receivers must stay awake for 54 time slots, or 17.28 ms, to ensure that they receive the packets of any sender during the backoff period. The time spent for idle listening with a CK of 50ms yields a duty cycle of about 35%, causing a rise in E_l, because the radio is listening idly for a long time, and in E_{MCU}, because the MCU is always on during the idle listening period.

In BMAC, E_l and E_{MCU} also dominate the overall energy consumption. E_l is high relative to transmission and reception energy consumption because of the long sampling period, which implies that the node spends more time listening to the channel than actually sending or receiving packets. This effect is despite the 10ms check interval set in the BMAC simulations that is meant to reduce idle listening. E_{MCU} is also high because all listening activity requires the MCU to be active. Note that E_t and E_r, which are an order lower than E_l, increase exponentially for nodes closer to the base station which are impacted more by the long preambles since they have more packets to forward. The switching energy in BMAC is also appreciable, since the radio switches state more frequently than the other 2 protocols.

In essence, the main benefit of RFIDImpulse is that it reduces the idle listening energy consumption and the microcontroller energy consumption significantly, which leads to major benefits for the overall energy consumption. The reduction in E_{MCU} is because RFIDImpulse allows the MCU to go into deep sleep mode, and to wake up on-demand whenever a packets is destined to this node. The reduction in E_l is because nodes do not wake up periodically to check the channel for activity. Instead, the nodes simply wait for an RFID wakeup message to activate their components which remain in power down mode otherwise. The tradeoff of RFIDImpulse is that it increases the switching energy for nodes with high forwarding traffic, as these nodes have to wake up their radios from deep sleep mode each time there is a packet to send or receive. The time and energy required for transition from deep sleep to active mode is larger than for BMAC and IEEE 802.15.4, where the voltage regulator of the radio is kept on. However, the switching energy of RFIDImpulse is still lower than that of BMAC, even for the node at hop count 1, because BMAC nodes switch back and forth between awake and idle mode much more often to sample the channel for activity.

Figure 4 exposes the energy tradeoffs of the three protocols in the six hop binary tree topology network for a high data rate scenario, in which S is 1 second. In this scenario, BMAC has the highest overall energy consumption for hop counts 1-3, and IEEE 802.15.4 has the highest energy consumption for hop counts 4-6. RFIDImpulse has the lowest energy consumption for hop counts 2-6, while the energy consumption at hop count 1 is about 50% higher than for IEEE 802.15.4.

For all three protocols, the progressive increase in energy consumption is apparent as we get closer to the base station. For BMAC, long preambles cause nodes to have significantly higher energy consumption than nodes located one hop further away from the base station. This is due to the increased transmission and reception energy components. The MCU energy consumption has almost the same impact for nodes at hop count 1, as the MCU is almost always on to send, receive, or check the channel. For nodes at hop count 1, the sleeping energy consumption is zero for BMAC, indicating channel saturation for this hop count.

RFIDImpulse exhibits a similar yet more pronounced increase in overall energy consumption due to the increased MCU activity and CCA actions for the large stream of packets. Most notably, the listening energy consumption for RFIDImpulse at hop count 1 is higher than that of BMAC, because the sheer packet volume arriving at this hop count

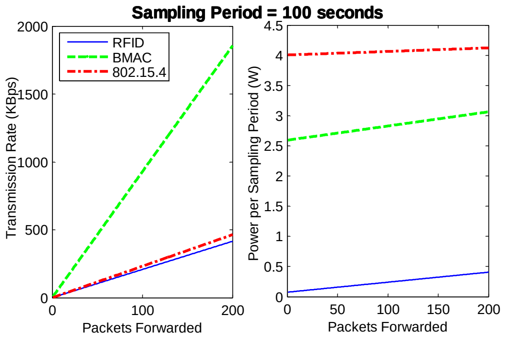

Fig. 5. Effective transmission rate and power consumption versus the number of packets forwarded

requires the nodes to listen for up to 54 time units each time to avoid collisions. As the MCU is always on while the radio is listening, the MCU energy consumption is also quite high for nodes closer to the base station.

The degradation in IEEE 802.15.4 is the most graceful among the three protocols for nodes closer to the base station, as the dominant energy components remain the MCU and listening energy consumption. The listening energy is still dominant because the nodes wake up periodically every 50 ms to check the channel for activity for 17.28 ms, during which the MCU is active. The main difference between RFIDImpulse and IEEE 802.15.4 is that the latter wakes up nodes anyway every 50 ms to check for activity. During the 54 time units in which nodes are active, several transmission can take place. In contrast, RFIDImpulse requires nodes to wake up for each packet and then go back to sleep. For all protocols, each time the node wakes up, we assume conservatively that it backs off twice before sending the packet, so every packet requires a 54 time unit listening time.

B. Optimal Traffic Load

Having explored the tradeoffs of RFIDImpulse relative to IEEE 802.15.4 and BMAC for low and high data rate scenarios, we now describe our simulations to determine the conditions for which RFIDImpulse performs better. It is obvious from the above discussion that the energy consumption of a particular node depends on S and the number of packets it forwards, which in turn determine the node's effective data rate.

Because of the dependence of energy consumption on both S and the number of forwarded packets, we now consider 4 fixed sampling periods and we vary the number of forwarded. The purpose here is to expose how the critical traffic load shifts for different sampling periods.

Figures 5-8 consider 4 different different sampling periods of 100, 10, 5, and 1 second respectively. The plots on the left side within each figure show the transmission rate for RFIDImpulse, BMAC, and IEEE 802.15.4. The plots on the right side show the corresponding energy consumption per sampling period.

Figure 5 corresponds to a sampling period of 100 seconds. The plot for BMAC exhibits the highest effective transmission rate because all packets in BMAC have long preambles (50 KB for a 10ms check interval). In contrast, the preambles for RFIDImpulse and IEEE 802.15.4 are only 4 and 16 bytes respectively, resulting in a much lower transmission rate for both protocols. RFIDImpulse has the lowest energy consumption for all considered numbers of forwarded packets, as it only turns on the radio and MCU for sending or receiving packets. BMAC outperforms IEEE 802.15.4 because BMAC only wakes up nodes for a time unit every 10ms whereas IEEE 802.15.4 wake up for 54 CCA units every 50ms.

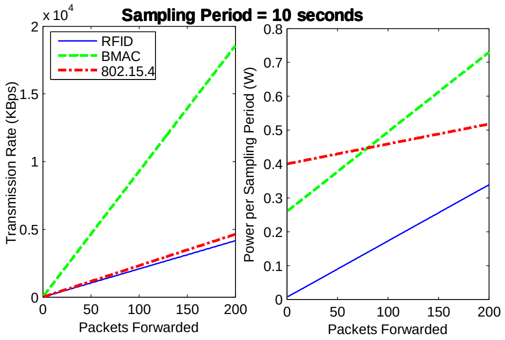

Fig. 6. Effective transmission rate and power consumption versus the number of packets forwarded

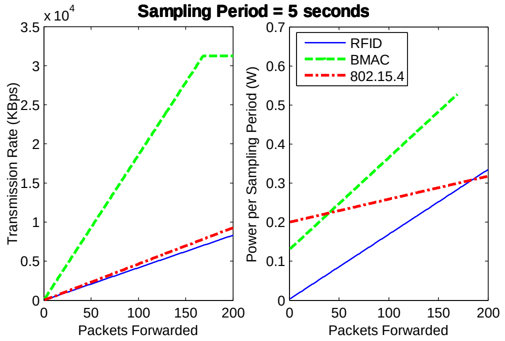

Fig. 7. Effective transmission rate and power consumption versus the number of packets forwarded

Figure 6 corresponds to a sampling period of 10 seconds. The effective transmission rate of BMAC is again up to four times higher than both RFIDImpulse and IEEE 802.15.4, whose effective transmission rates are almost the same. The increased sampling frequency, however, changes the relative energy consumption of the three protocols. RFIDImpulse still has the lowest energy consumption per sampling period for all considered forwarding loads, but the difference in energy consumption relative to IEEE 802.15.4 and BMAC shrinks. This is because, as mentioned above, energy consumption per sampling period of RFIDImpulse is not highly dependent on the S, whereas the shorter S translates into fewer check intervals for both BMAC and IEEE 802.15.4. For S of 10 seconds, BMAC outperforms IEEE 802.15.4 only for lower traffic loads due to increasing impact of long preambles for high traffic loads.

Figure 7 considers a S of 5 seconds. The effective transmis-

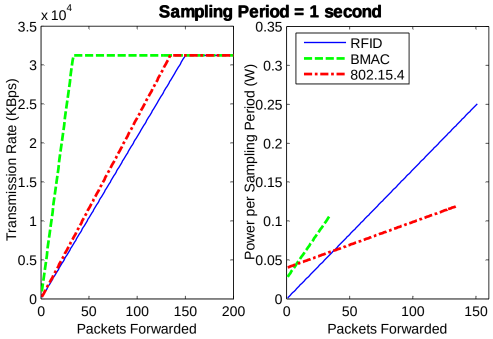

Fig. 8. Effective transmission rate and power consumption versus the number of packets forwarded

sion rate of BMAC reaches the maximum radio transfer rate, causing packets to be dropped if a node has more than 168 packets to forward during the sampling period. The effective transmission rates for RFIDImpulse and IEEE 802.15.4 remain lower than 10 Kilo Bytes per second. The smaller S of 5 seconds also changes the relative energy consumption of the three protocols. RFIDImpulse outperforms IEEE 802.15.4 as long as the number of forwarded packets is lower than 184, while IEEE 802.15.4 has lower energy for higher traffic loads. This effect is due to the increasing switching energy, MCU energy, and idle listening components for RFIDImpulse, that is proportional to the number of packets forwarded by a node (see Figure 4). As for BMAC, it only outperforms IEEE 802.15.4 if the number of forwarded packets is less than 40.

Finally, Figure 8 considers a short sampling period of 1 second, which causes radio saturation for all three protocols, as the effective transmission rate reaches the maximum radio transfer rate. Saturation occurs at 34 forwarded packets for BMAC, 134 packets for IEEE 802.15.4, and 151 packets for RFIDImpulse. The saturation point relates directly to the control overhead of the packets in each protocol. BMAC uses a long preamble for maintaining asynchronous duty cycles, so it has the lowest saturation point. IEEE 802.15.4 uses a typical header of 16 bytes, so it has a much higher saturation point. RFIDImpulse uses 4 bytes for identifying which tag to activate, so it has the highest saturation point. Regarding energy consumption, the crossover points of BMAC and RFIDImpulse with IEEE 802.15.4 exhibit a shift in favor of the latter for an increase sampling frequency. RFIDImpulse now outperforms IEEE 802.15.4 for forwarding loads up to 37 packets, after which IEEE 802.15.4 has lower energy consumption. However, note that RFIDImpulse has a higher saturation point than IEEE 802.15.4. For high traffic loads, IEEE 802.15.4 begins to drop packets due to saturation, whereas RFIDImpulse can support up to 151 forwarded packet per sampling period.

VI. DISCUSSION

The results of the performance evaluation section reveal that RFIDImpulse outperforms both BMAC and IEEE 802.15.4 for low and medium traffic scenarios by reducing idle listening and MCU energy consumption. In high traffic scenarios, IEEE 802.15.4 slightly outperforms RFIDImpulse, but the saturation point of RFIDImpulse is higher. A potential optimization of RFIDImpulse is to allow a node to stay awake for multiple packet transmissions rather than waking up for every packet when the traffic load is high.

The results also identify the optimal operating region and crossover point of each of the protocols for given traffic loads. These results can form the basis of an adaptive RFIDImpulse mechanism by which a node can autonomously decide to use RFIDImpulse for low forwarding traffic. This can be determined on the fly through the analytical model in Section IV. If the forwarding traffic at a node exceeds the crossover point, the node can seamlessly switch to using plain IEEE 802.15.4, by simply refraining from using RFID readers and tag as wake up radio. For very high traffic loads where IEEE 802.15.4 saturates, the node can switch back to RFIDImpulse to avoid dropping any packets.

As a mechanism that coordinates with the MAC protocol, RFIDImpulse does not perform any network-wide scheduling. As such, the protocol's performance can benefit from the use of a higher layer scheduling mechanism, for example to avoid switching on and off continuously when the traffic load is too high or when there is a burst stream of packets to forward.

REFERENCES

[1] R. Want *Enabling ubiquitous sensing with RFID*, *Computer journal*, IEEE Computer Society, vol. 37, pp 84-86, 2004.
[2] *Atmel Atmega128*, *http://www.atmel.com*.
[3] *TI cc2420 radio transceiver*, *http://focus.ti.com/docs/prod/folders/print/cc2420.html*.
[4] W. Ye, J. Heidemann, and D. Estrin, *Medium access control with coordinated adaptive sleeping for wireless sensor networks*, *IEEE/ACM Transactions on Networking* **3** (2004), 493–506.
[5] T. V. Dam & K. Langendoen, An adaptive energy efficient mac protocol for wireless sensor networks, *ACM Sensys* (2003).
[6] J. Polastre, J. Hill, and D. Culler, Versatile low power media access for wireless sensor networks, (2004), 95–107.
[7] R. Jurdak, P. Baldi, and C.V. Lopes. "Adaptive Low Power Listening for Wireless Sensor Networks,"*IEEE Transactions on Mobile Computing.* Volume 6, 2007.
[8] I. Rhee, A. Warrier, M. Aia, and J. Min, Z-mac: a hybrid mac for wireless sensor networks, *In proc. Sensys05* (New York, USA), 2005, pp. 90–101.
[9] A.G. Ruzzelli, G.M.P O'Hare and R. Jurdak, MERLIN: Cross-Layer Integration of MAC and Routing for Low Duty-Cycle Sensor Networks, *Ad Hoc Networks journal, Elsevier* 2008 (in press).
[10] G. Lu, B. Krishnamachari, and C. S. Raghavendra, An adaptive energy-efficient and low-latency mac for data gathering in sensor networks, *In proc. of International workshop on Algorithms for Wireless, Mobile, ad Hoc Sensor Networks* (2004).
[11] Miklós Maróti and Branislav Kusy and Gyula Simon and Ákos Lédeczi, The flooding time synchronization protocol, In proc. *ACM SenSys '04*, 2004.
[12] L. Gu and J.A. Stankovic, Radio-Triggered Wake-Up Capability for Sensor Networks, *Proceedings of the 10th IEEE RTAS* (2004).
[13] J. da Silva, Jr. and J. Shamberger et. al., Design methodology for PicoRadio networks, *DATE '01*, (2001).
[14] J. Hill and D. Culler, A wireless embedded sensor architecture for system-level optimization, *Technical report, U.C. Berkeley,* 2001.
[15] Tag Sense: RFID and Wireless Sensing *http://www.tagsense.com/*
[16] ISO standard technical committees *http://www.iso.org/iso/standards_development/*
[17] P. Skraba, Hamid Aghajan, Ahmad Bahai, RFID Wake-up in Event Driven Sensor Networks, *Technical report, U.C. Berkeley,* 2001.
[18] A.G. Ruzzelli, R. Jurdak, and G.M.P. O'Hare, On the RFID wake-up impulse for multi-hop sensor networks, In proceedings of (SenseID) Workshop at (*ACM SenSys 2007*), Sydney, Australia. November, 2007.
[19] A.G. Ruzzelli, P. Cotan, G.M.P. O'Hare, R.Tynan, and P.J.M Havinga, Protocol assessment issues in low duty cycle sensor networks: The switching energy, In Proc. *IEEE (SUTC2006)*, Taichung, Taiwan. June, 2006.
[20] IEEE 802.15.4 MAC/Phy standard for low-rate wireless personal area networks (LR-WPAN's) *http://www.ieee802.org/15/pub/TG4.html*