TR-MAC: An Energy-Efficient MAC Protocol for Wireless Sensor Networks exploiting Noise-based Transmitted Reference Modulation

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Abstract. Energy-constrained behavior of sensor nodes is one of the most important criteria for successful deployment of wireless sensor networks. The medium access control (MAC) protocol determines the time a sensor node transceiver spends listening or transmitting, and hence the energy consumption of the overall node. Transmitted reference (TR) modulation as the underlying physical layer provides new opportunities and challenges to be explored in the MAC layer. To utilize the advantages and overcome the challenges provided by the TR modulation, a new energy-efficient MAC protocol TR-MAC that uses noise-based carrier for wireless sensor networks is proposed in this paper. TR-MAC realizes multiple access using individual frequency offsets for a pair of nodes, allows both transmitter-driven and receiver-driven communication and is suitable for asynchronous low data rate application. TR-MAC enables energy-driven communication since nodes can adapt their duty cycle based on available energy, thus the protocol becomes energy-efficient.

Keywords: TR modulation, energy-efficiency, MAC protocol, TR-MAC

1 Introduction and Motivation

The Medium Access Control (MAC) protocol is responsible for addressing and providing a channel access mechanism to enable various nodes within a network to communicate with each other in a shared wireless communication medium. The physical layer underlying the MAC layer modulates the data to the reference signal in order to send it with a specified frequency through the medium. As opposed to regular modulation techniques, Transmitted Reference (TR) modulation [1] not only sends the modulated signal, but also sends the reference signal with a known time offset, as presented in Fig. 1 on the left. Following this, a receiver can restore the original data by correlating the received signal with a delayed version of itself with the same time offset since all multi-path components contain identically distorted pulses with consistent mutual delay. This interesting property of TR modulation allows to use noise as information carrier that is also easy to generate [2]. The receiver can restore the original signal without rake receiver or channel state information or power-hungry stable oscillators.

Consequently, the signal acquisition process becomes faster allowing for shorter synchronization time, giving a potential for reducing power consumption. Furthermore, frequency offsets can be used in place of time offsets, because the former are easier to implement on a chip [2]. Moreover, multiple nodes can transmit simultaneously by employing various frequency offsets without the need for mutual timing coordination. Therefore, TR modulation is suitable for asynchronous low data rate communication offering additional flexibility to the upper MAC layer. However, TR modulation consumes more power than a general modulation technique to transmit individual bits since the reference signal is also sent.
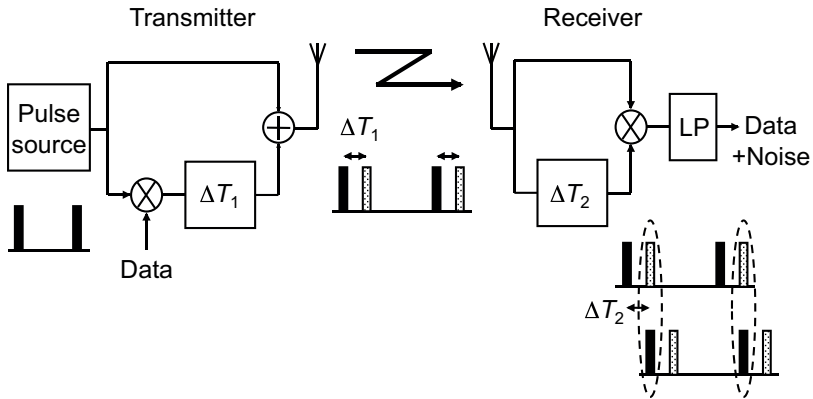

Fig. 1. Transmitted Reference modulation

In this paper we will investigate how we can optimally exploit the characteristics of TR modulation at the MAC layer in order to realize a wireless sensor network technique compatible with energy harvesting. We introduce a new MAC layer protocol, called TR-MAC, to exploit all the advantages provided by the TR modulation technique minimizing its drawbacks. Instead of sending long preambles to inform a receiver that wakes up about an upcoming data packet, TR-MAC sends data right away with a very short preamble as data packets in wireless sensor networks are generally very small. Moreover, the transmitter listens for acknowledgement from receiver after sending each data burst. Thus the transmitter is able to reduce the length of the consecutive data-listen bursts if it receives an acknowledgement from the receiver for unsynchronized links. When the link between a node pair becomes synchronized, then communication in TR-MAC can be transmitter-driven or receiver-driven as both the transmitter and receiver store each other's next wake up time. Finally, TR-MAC enables energy-driven communication by allowing the nodes to adapt their duty cycle based on the local energy availability.

The contributions of this paper are as follows: (1) we introduce a MAC protocol, TR-MAC, exploiting the characteristics of TR modulation; (2) we provide

basic models to analyze the energy consumption of this MAC protocol and two reference protocols; and (3) we evaluate the energy consumption and show that the introduced MAC protocol in combination with TR modulation compares favorably to the reference protocols.

This paper is organized in 6 sections. Related work in Section 2 is followed by TR-MAC protocol design in Section 3. Afterwards, Section 4 describes the TR-MAC modeling and Section 5 gives the results and analysis. Finally, Section 6 provides our conclusions and future work.

2 Related Work

In this section, we will analyze existing MAC protocols from the perspective of energy-efficiency. The proposed MAC protocols in the literature are classified into three categories: reservation-based, protocols with common active period, and asynchronous preamble sampling MAC protocols by [3]. After extensive analysis, the authors of [3] claimed that preamble sampling protocols are the most energy efficient category of MAC layer protocols. The preamble sampling protocols allow the nodes to wake up and sleep independently of the other nodes, thus they are termed Low Power Listening (LPL) protocols. However, the receiver has to wake up periodically to check for data transmission in the channel. The transmitter precedes the data packet with a preamble of maximum length equal to the receiver's sleep or check interval whenever it wishes to send any data. If the receiver detects some activity in the channel during its periodic wake up time, it continues to listen in order to receive the data from the transmitter. Compared to the other categories, the preamble sampling protocols have a greater energy saving capability with less need for network-wide management, thus are very suitable for low data rate asynchronous applications.

The preamble sampling protocols can be realized in three ways as mentioned in [3], and the references therein. Firstly, the transmitter can replace the long preamble by short preamble packet bursts with destination address to allow the target receiver to wake up later to receive data, whereas a non-target receiver can go back to sleep after receiving a single burst. Alternatively, the transmitter can send preamble-listen bursts to shorten its preamble length by an acknowledgement from the intended receiver if it wakes up. However, these protocols do not adapt preamble length for future transmissions and do not send any acknowledgement after successful data transmission. Protocols like X-MAC [4], SpeckMAC-B [5], ContikiMAC [6] are examples of this category of MAC protocols. We take X-MAC [4] as a reference protocol of this category. Secondly, the transmitter can adapt its preamble length by remembering the receiver's wake up time for forthcoming communications. However, these receiver-driven protocols are unfavorable for broadcast traffic where one transmitter has to wake up multiple times for its multiple neighbors. Furthermore, these protocols have to send the longest possible length of preamble for the first time communication. WiseMAC [7], CSMA-MPS [8], TrawMAC [9], SyncWUF [10] falls into this category. We take WiseMAC [7] as a reference for this class of protocols. Finally,

there are some protocols where the sensor node can adapt its duty cycle based on requests from the neighborhood, traffic load, or topology information. Nevertheless, these duty cycle adaptable protocols are suitable only for application specific scenarios, not for all scenarios; and they have no mechanism to adapt the communication based on energy availability on individual nodes.

3   TR-MAC Protocol Design

As introduced in Section 1, TR modulation is characterized by fast synchronization, allowing for the use of very short preambles; and inherent multiplexing, allowing for implicit identification of possibly simultaneous transmissions. To exploit these characteristics, and to mitigate the transmit power penalty of TR modulation, a new energy-efficient protocol, TR-MAC, is proposed that combines the best characteristics from all three categories of preamble sampling protocols. TR-MAC allows the receiver to detect any transmission in the channel with a very short preamble because of the inherent benefit provided by underlying TR modulation. Moreover, small data packet can be included in the preamble as the data packets in wireless sensor networks are generally very small, within a range of few bytes. As the preamble is a part of the data packet and TR-MAC sends data right away with the preamble, therefore from now on preamble-data will be referred as only data in this paper.

TR-MAC sends data multiple times to deal with uncertainty regarding the receiver's wake up time. Furthermore, just one bit in the data packet is enough to instruct the receiver to continue listening in case more large data packets are following the initial small ones. As transmission is costly for TR modulation, therefore TR-MAC introduces some listen periods just after every data packet where the transmitter listens the medium for acknowledgement from the receiver. Thus the transmitter minimizes the total data-listen duration based on the reception of acknowledgement from the receiver for first time communications. After first time communication, both transmitter and receiver synchronize their future communication by storing each other's next periodic wake up time to reduce the data-listen duration in order to save energy. Hence data transmission can be either transmitter-driven or receiver-driven when the link is synchronized between a pair of nodes, thus giving a considerable flexibility to the upper layers. Moreover, the duty cycle of a sensor node can be adapted based on either the available energy on nodes or application requirement. Therefore the newly proposed TR-MAC protocol is energy-driven, thus energy-efficient. Multiple access is another critical issue to address for any wireless sensor networks. Nodes following the traditional MAC protocols adapt their transmit times to deal with multiple transmitters attempting to access the channel simultaneously. However, the new TR-MAC protocol achieves multiple access using individual frequency offsets for a pair of nodes, a key advantage created by the underlying TR modulation. Hence collision can be avoided as future communication will take place in different virtual channels by using different frequency offsets.

The newly proposed TR-MAC protocol has three states, as shown in Fig. 2, namely (1) first time communication; (2) unsynchronized link; and (3) synchronized link. In the first stage for first time communication, a node does not have any information about its neighbors. Thus one node transmits data-listen bursts in the default frequency offset if it wants to send any data. The receiver periodically listens to the default frequency offset to detect any data transmission, like other preamble sampling protocols. When the intended receiver wakes up and receives a single the data burst, then it responds with an acknowledgement indicating a successful transmission. In this stage, the nodes perform the process of neighbor discovery, exchange the full MAC address, establish a link identifier and agree on the frequency offset to be used in the following communications.
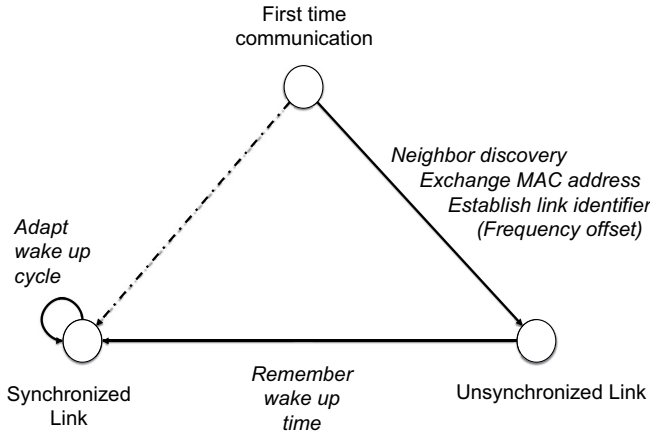

Fig. 2. TR-MAC: Three states

After the first time communication, the protocol moves to the next, unsynchronized link stage, as presented in Fig. 3. During this stage, the transmitter sends short data-listen bursts at the previously agreed upon frequency offset until it receives an acknowledgement from the receiver. The receiver listens to the agreed frequency offset for any data transmission. If the receiver is able to detect any data packet, then it can derive the link identifier from the listening offset and preamble of the data packet. A very small preamble is enough to detect any transmission in the channel because of the TR modulation. The receiver's next wake up time is specified in the acknowledgement packet indicating whether the check interval will be a normal one, or a half or double of the previous one based on traffic load or application requirement. Also a request for the transmitter to acknowledge in its next communication whether the transmitter will follow it or not is indicated. The transmitter mentions whether it agrees or not on the proposed time in its next transmission. Hence the nodes decide whether future communication will be transmitter-driven or receiver-driven. At this point, the
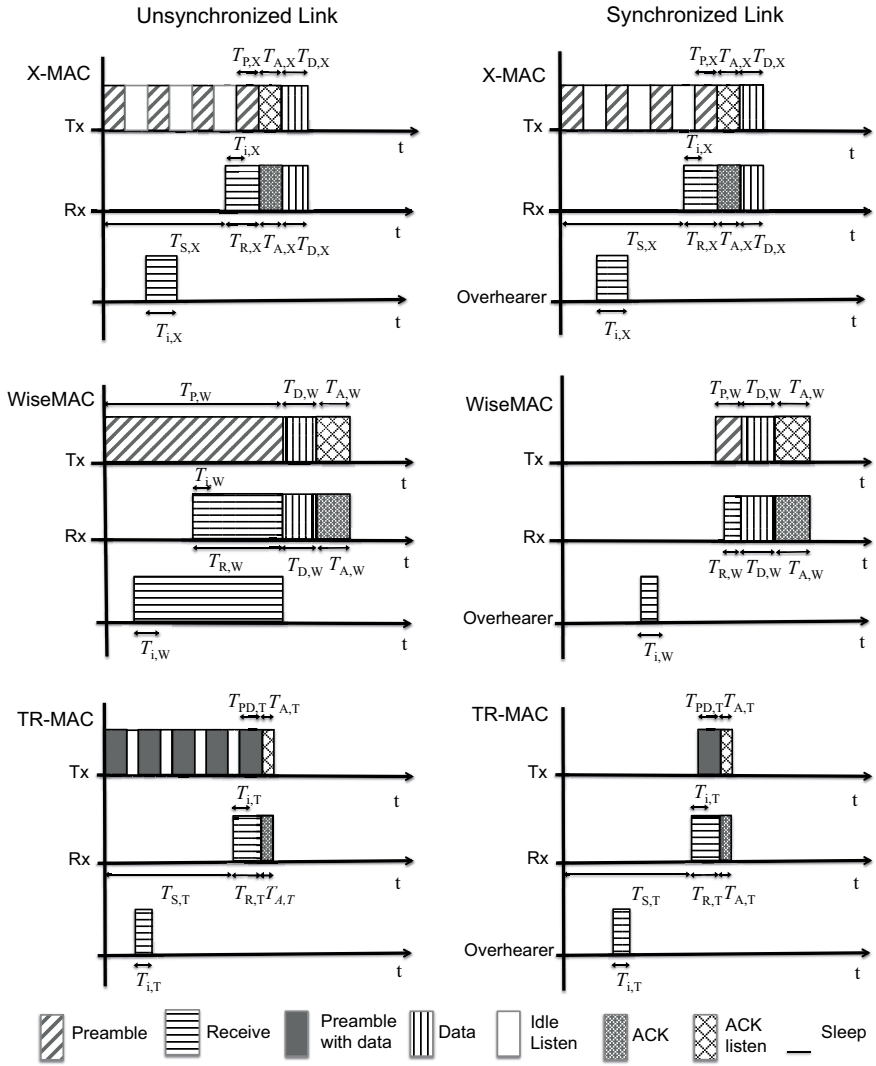
Fig. 3. Comparison of MAC Protocols

protocol advances to its final synchronized link stage where the link between a pair of node is synchronized, as shown in Fig.3. During this stage, the nodes already know the frequency offset and the specific time to wake up to reach a particular node, thereby optimally minimizing the data-listen burst length to as minimum as possible. Moreover, in this final stage, the nodes can adapt their duty cycles to meet the requirements of the network or another node having less energy to increase network lifetime. A new node joining the network sometimes can move to synchronized stage skipping the unsynchronized stage if the link identifier can be finalized between a pair of nodes.

The use of both transmitter-driven and receiver-driven duty cycling provides some interesting opportunities to realize energy-efficient multi-hop communications at the network level. For instance, TR-MAC is able to create a ripple effect while broadcasting still maintaining its energy efficiency. The transmitter can instruct its first hop neighbors to follow its lead and those can in turn instruct their respective neighbors to follow them in order to broadcast more efficiently: saving both energy and time. Finally, a system of Green Waves [11] can be created to deliver packets to their destinations with limited delay.

4 Modeling

In this section, we present a mathematical representation of TR-MAC for unsynchronized links in terms of energy consumption to send or receive a packet and for periodic listening. We also derived the analytical models for X-MAC and WiseMAC for the previously mentioned scenarios and compared with that of TR-MAC. The comparison results are presented in Section 5. In the symbols below, we use the comma separated subscript T, X, W to denote a symbol specific for TR-MAC, X-MAC and WiseMAC respectively. If the subscript is omitted, the symbol applies to multiple or all three MAC protocols.

To model the energy consumption to send or receive a packet, lets consider P_{Tx}, P_{Rx} and P_{S} to represent power to send, receive and sleep having values 1 mW, 1 mW and 15 μW respectively. TR-MAC sends both reference and modulated signals, thus its power level $P_{\mathrm{Tx,T}}$ is 2 mW. The data rate is considered as 25 kbps and a single data packet duration is considered with 32 bits having duration 1.28 ms. T_{W} represents the periodic check interval that is a summation of sleep duration, T_{S}, and periodic listen duration, T_{i}. The power consumption and time for switching from sending to receiving and vice-versa are much smaller compared to the other values, and are neglected in our modeling. The TR-MAC data packet, $T_{\mathrm{PD,T}}$, consists of 8 bits of preamble, $T_{\mathrm{P,T}}$, 16 bits of header, T_{H}, followed by 32 bits of data, T_{Data}, thus having 56 bits with duration 2.24 ms. We also consider the preamble duration, $T_{\mathrm{P,T}}$, is enough for the receiver to detect any transmission in the channel because of the inherent advantage provided by the TR modulation. The acknowledgement packet, $T_{\mathrm{A,T}}$, consists of 8 bits preamble, $T_{\mathrm{P,T}}$, and 16 bits header, T_{H}, in total 24 bits having duration .96 ms. The data packets of X-MAC and WiseMAC, $T_{\mathrm{D,X}}$ and $T_{\mathrm{D,W}}$ respectively, includes 16 bits header, T_{H}, and 32 bits data, T_{Data}, thus have 48 bits with dura-

tion 1.92 ms. The symbols and values for TR-MAC, X-MAC and WiseMAC are given in Table 1. The values used for TR-MAC reflect the main characteristics of TR-MAC, i.e., its very short preamble at the cost of increased transmission power.

Table 1. System parameters

Parameters	TR-MAC	X-MAC [4]	WiseMAC [7]
Preamble duration, T_P	8 bits (.32 ms)	65 bits (2.6 ms)	T_W
ACK duration, T_A	24 bits (.96 ms)	65 bits (2.6 ms)	80 bits (3.2 ms)
Header duration, T_H	16 bits (.64 ms)	16 bits (.64 ms)	16 bits (.64 ms)
Data duration, T_{Data}	32 bits (1.28 ms)	32 bits (1.28 ms)	32 bits (1.28 ms)
Data+header duration, T_D	56 bits (2.24 ms)	48 bits (1.92 ms)	48 bits (1.92 ms)
Power to send, P_{Tx}	2 mW	1 mW	1 mW
Power to receive, P_{Rx}	1 mW	1 mW	1 mW

All these preamble sampling protocols have the periodic listen as their background energy consumption, E_{PL}, given by Eq. 1. Here the periodic listen of TR-MAC, X-MAC and WiseMAC are $T_{i,T}$, $T_{i,x}$ and $T_{i,W}$ respectively and the sleep duration are $T_{S,T}$, $T_{S,X}$ and $T_{S,W}$ respectively.

$$E_{PL} = \frac{P_{Rx}T_i + P_S T_S}{T_S + T_i} \qquad (1)$$

TR-MAC periodic listen duration, $T_{i,T}$, has to be greater than or equal to the duration of the acknowledgement duration, $T_{A,T}$, plus two times preamble duration, $T_{P,T}$, in order to detect a data transmission in the medium given by

$$T_{i,T} \geq T_{A,T} + 2T_{P,T}. \qquad (2)$$

We take the minimum duration for the periodic listen of TR-MAC in our calculation to minimize power consumption because that is enough to detect a transmission. Similarly the condition for periodic listen X-MAC is given by Eq. 3 and we take the minimum value of $T_{i,X}$ for calculation.

$$T_{i,X} \geq T_{A,X} + 2T_{P,X} \qquad (3)$$

For WiseMAC, the minimum listen duration, $T_{i,W}$, is taken as the minimum preamble duration, $T_{P,T}$, because the receiver keeps listening in case it detects any transmission in the channel. Therefore, the periodic listen for TR-MAC is taken as 40 bits with duration 1.6 ms, for X-MAC is taken as 195 bits with duration 7.8 ms and for WiseMAC is taken as the minimum duration to detect any transmission, that is 8 bits with duration .32 ms, respectively.

The expected energy to send a single packet for TR-MAC, $E_{\text{Tx,T}}$, is given by Eq. 4 and is derived as follows. The energy required for a single cycle of sending a packet of preamble and data, followed by listening for an acknowledgement (regardless of its receipt) is given by $P_{\text{Tx,T}}T_{\text{PD,T}} + P_{\text{Rx}}T_{\text{A,T}}$. Always at least one such cycle is needed for sending the data, hence the +1. Extra cycles might be needed depending on when the receiver wakes up. If we assume that the first cycle of sending a packet will start at an arbitrary moment between the start of two consecutive listen periods with duration $T_{\text{i,T}} + T_{\text{S,T}}$, we can derive the expected number of extra cycles. If the packet starts within the first $T_{\text{i,T}} - T_{\text{P,T}}$ seconds of the listen period of the receiver, no extra cycles are needed as the receiver will receive the complete preamble from which it can derive that it needs to stay awake for the rest of the packet. If the packet transmission starts later, with probability $(T_{\text{S,T}}+T_{\text{P,T}})/(T_{\text{i,T}}+T_{\text{S,T}})$, extra cycles will be transmitted until the next listen period of the receiver. On average, the number of extra cycles will be $\frac{1}{2}(T_{\text{S,T}}+T_{\text{P,T}})/(T_{\text{PD,T}}+T_{\text{A,T}})$. The energy needed to send a packet is thus given by

$$E_{\text{Tx,T}} = \left(\frac{1}{2} \cdot \frac{(T_{\text{S,T}} + T_{\text{P,T}})^2}{(T_{\text{i,T}} + T_{\text{S,T}})(T_{\text{PD,T}} + T_{\text{A,T}})} + 1 \right) (P_{\text{Tx,T}}T_{\text{PD,T}} + P_{\text{Rx}}T_{\text{A,T}}). \quad (4)$$

In addition to the periodic listen energy, the receiver has to spend extra energy to receive a packet. To calculate this additional energy, the periodic listen duration, $T_{\text{i,T}}$, has to be subtracted from the expected extended listening duration, $\overline{T}_{\text{R,T}}$, for the reception of the data packet. Furthermore, the energy to send an acknowledgement has to be added. The additional energy to receive a packet $E_{\text{Rx,T}}$ is given by

$$E_{\text{Rx,T}} = P_{\text{Rx}} \left(\overline{T}_{\text{R,T}} - T_{\text{i,T}} \right) + P_{\text{Tx,T}}T_{\text{A,T}}. \quad (5)$$

The receiver listen duration has to be at least the duration of a data packet, and it can be extended up to the acknowledgement packet duration plus two times data packet duration depending on the random wake up time of the receiver. It is given by

$$T_{\text{A,T}} + 2T_{\text{PD,T}} > T_{\text{R,T}} \geq T_{\text{PD,T}}. \quad (6)$$

Given that the wake-up time of the receiver is uniform by distributed over the interval, the expected extended listening duration, $\overline{T}_{\text{R,T}}$, is given by

$$\overline{T}_{\text{R,T}} = \int_{t=T_{\text{PD,T}}}^{T_{\text{A,T}}+2T_{\text{PD,T}}} tP(T_{\text{R,T}} = t)dt = \frac{1}{2}T_{\text{A,T}} + \frac{3}{2}T_{\text{PD,T}}, \quad (7)$$

which is taken as 104 bits with duration 4.16 ms for calculation.

Similarly, the expected energy to send a packet for X-MAC, $E_{\text{Tx,X}}$, is derived like TR-MAC and given by Eq. 8 with the exception that X-MAC needs to send the data packet separately.

$$E_{\text{Tx,X}} = \left(\frac{1}{2} \cdot \frac{(T_{\text{S,X}} + T_{\text{P,X}})^2}{(T_{\text{i,X}} + T_{\text{S,X}})(T_{\text{P,X}} + T_{\text{A,X}})} + 1 \right)(P_{\text{Tx,X}}T_{\text{P,X}} + P_{\text{Rx}}T_{\text{A,X}})$$
$$+ P_{\text{Tx,X}}T_{\text{D,X}} \tag{8}$$

And the additional energy to receive a packet for X-MAC does not have the energy to receive a preamble because that is already calculated within the periodic listen energy. Therefore only the energy to send an acknowledgement and the energy to receive the data packet is present in the expression to calculate the additional energy to receive a packet, $E_{\text{Rx,X}}$, given by

$$E_{\text{Rx,X}} = P_{\text{Tx,X}}T_{\text{A,X}} + P_{\text{Rx}}T_{\text{D,X}}. \tag{9}$$

Finally, the expected energy to send a packet for WiseMAC, $E_{\text{Tx,W}}$, includes the energy to send a preamble, then to send the data and later to receive the acknowledgement,

$$E_{\text{Tx,W}} = P_{\text{Tx,W}}T_{\text{P,W}} + P_{\text{Tx,W}}T_{\text{D,W}} + P_{\text{Rx}}T_{\text{A,W}}. \tag{10}$$

The receiver has to spend additional energy $E_{\text{Rx,W}}$ to listen for the preamble, then to listen for the data packet, at last to send the acknowledgement. So,

$$E_{\text{Rx,W}} = P_{\text{Rx}}\left(\overline{T}_{\text{R,W}} - T_{\text{i,W}}\right) + P_{\text{Rx}}T_{\text{D,W}} + P_{\text{Tx,W}}T_{\text{A,W}}, \tag{11}$$

where the average receiver listen duration is $\overline{T}_{\text{R,W}} = \frac{T_{\text{W}}}{2}$.

5 Results and Analysis

We compute the analytical models of TR-MAC, X-MAC and WiseMAC for unsynchronized links in Matlab in order to compare their energy consumption to send or receive a packet and for background energy in periodic listening. We vary the check interval duration, T_{W}, for these protocols and measured the energy consumption. The symbols and corresponding values are given in Section 4 and Table 1. Fig. 4 depicts the energy to send a packet. It can be observed that TR-MAC consumes less energy than WiseMAC even though TR-MAC needs more power to transmit a single packet. The reason is that TR-MAC adapts its total data-listen duration based on acknowledgement from receiver whereas WiseMAC sends a full preamble of length equal to the check interval duration T_W. However, X-MAC has less energy consumption than TR-MAC because of the underlying

TR modulation technique that needs more power to transmit both reference signal and the modulated signal. Nevertheless, we expect to have advantage over X-MAC because unlike X-MAC, TR-MAC has defined synchronized links where the transmitter is able to adapt the start of the data-listen sequence to an optimized value based on the receiver's next wake up time.
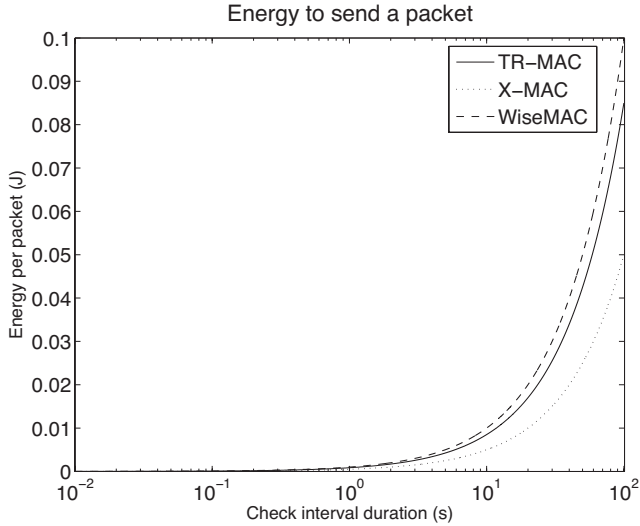

Fig. 4. Energy to send a packet

The total energy spent at the receiver side can be divided in two parts: periodic listen and additional energy to receive a packet, presented consecutively in Fig. 5 and Fig. 6. The periodic listen energy in Fig. 5 shows that TR-MAC is better than X-MAC as TR-MAC is capable of detecting transmission with a smaller preamble, thus the listen duration can be smaller. Also the smaller acknowledgement duration in TR-MAC allows to have smaller periodic listen duration. Nevertheless, WiseMAC seems better than TR-MAC having small periodic listen duration. However, WiseMAC overhearers will spend much energy for receiving a packet since they have to listen the whole preamble duration if they detect any communication in the channel in order to receive the data afterwards. For each packet sent, an overhearer spends the additional energy shown in Fig. 6. However, a TR-MAC overhearer can go back to sleep just after receiving a single data burst. So no extra energy is spent by overhearers in TR-MAC besides the energy consumption shown in Fig. 5. Thus TR-MAC will spend much less energy in the long run though WiseMAC has better performance for background energy consumption due to periodic listen. Fig. 6 represents the additional energy consumption of the protocols to receive a packet where the curves for TR-MAC and X-MAC overlap and show very small energy consumption, but
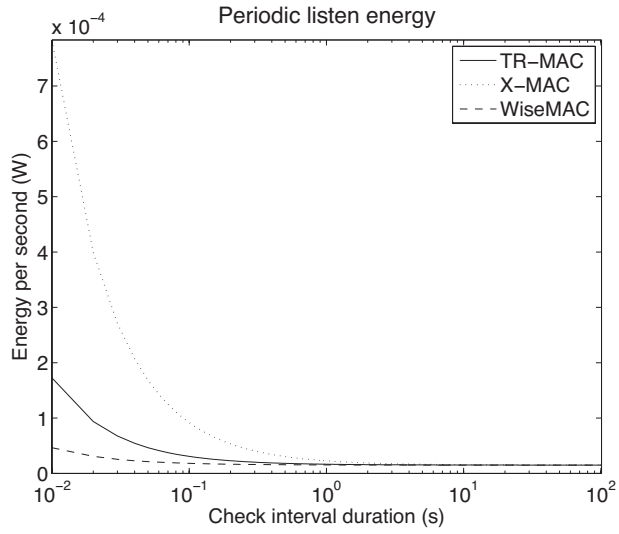
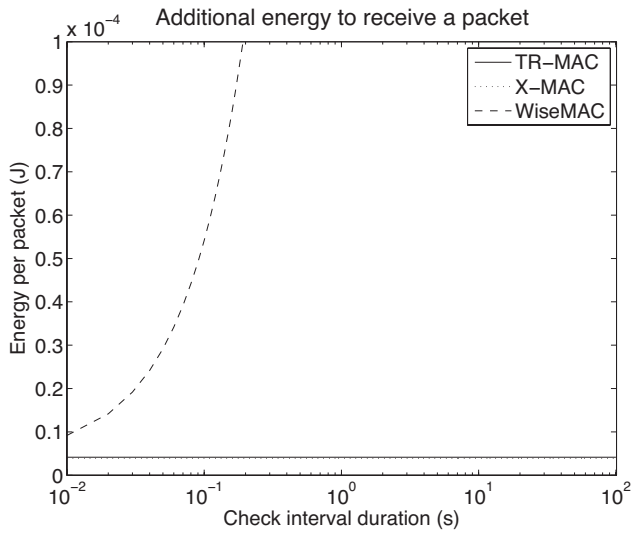**Fig. 5.** Periodic listen energy

Fig. 6. Additional energy to receive a packet

WiseMAC consumes much energy as a receiver and a potential overhearer has to listen on average half of the check interval duration in order to receive a packet.

6 Conclusions and Future Work

The TR-MAC with noise-based TR modulation underneath is an energy-efficient MAC protocol suitable for short-range, low data rate applications that utilizes all the usefulness of TR modulation while minimizing its drawbacks. TR-MAC has many attractive characteristics. A transmitter using TR modulation can use noise as information carrier and a receiver can save energy by faster synchronization time without power hungry stable oscillators. In addition, TR-MAC is capable of sending data right away without long preambles and receivers can detect transmission by listening to the specified offset with the link identifier. Moreover, nodes can adapt their duty cycle based on available energy, thus the protocol is totally energy-driven. Furthermore, TR-MAC can be both transmitter-driven and receiver-driven based on the application requirement, thus gives much opportunities for energy-efficient routing in the network layer.

We modeled and compared the unsynchronized links stage of TR-MAC with X-MAC and WiseMAC. It turns out that TR-MAC has a very low energy consumption for periodic listening, which is not affected by overhearing transmission for other receivers, as in the case of WiseMAC. Furthermore, similar to X-MAC but contrary to WiseMAC, TR-MAC needs very little energy to receive a packet. Finally, transmitting a packet is more costly than in X-MAC, but this can be compensated by choosing a shorter check interval. Overall, TR-MAC is very promising for energy-efficient communications in noisy environments, where only a limited amount of data is transmitted between a single pair of nodes.

As our future work, we will model the synchronized link stage for TR-MAC and compare with X-MAC and WiseMAC. We expect to have better performance for synchronized link stage as TR-MAC has interesting features for that. In addition, we will compare TR-MAC with some other protocols that send data instead of preamble. We will also evaluate TR-MAC with traffic adaptivity in multi-hop networks. Finally, energy harvesting will be incorporated in future by letting transmitters and receivers adapt their duty cycle based on locally available energy.

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