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DCW-MAC: An energy efficient medium access scheme using duty-cycled low-power wake-up receivers

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***Abstract*—In this work we present a new low-power medium access scheme for sensor-type networks specifically with low traffic intensity. We call the proposed scheme DCW-MAC where ultra-low-power wake-up receivers are combined with optimal duty-cycled listening. First we introduce a framework for the analysis of energy consumption of the studied network type, then we use it to optimize the MAC scheme to achieve very low total energy consumption per transmitted data packet. It is shown that even with large sacrifices in terms of wake-up receiver detection performance, required to achieve ultra-low-power consumption with a limited form factor, we can achieve very competitive total energy consumption and outperform other MAC schemes for scenarios with low traffic.**

I. Introduction

Energy efficiency is a key design issue for wireless sensor network (WSN) applications. In these applications energy resources are severely limited, both due to node sizes and possible placements in locations where batteries cannot easily be replaced. To design a long lifetime network, it is important both to design low-power transceivers and to use energy efficient protocols to control the communication. In general, the dominant sources of energy waste in a communication system include, but are not limited to, *idle listening*, *collisions*, *data overhead* and *overhearing* [1]. These energy costs are reduced to a large extent by designing an energy efficient medium access control (MAC) protocol.

In this paper we focus on the principle of duty-cycled MAC protocols, which is a very common approach to reduce energy cost in the design of low power communication systems [1]–[3]. In this approach the idle listening, which is the dominant factor for energy consumption, is reduced by only listening for transmissions at certain time instants and turning off the transceiver at other time instants. Several different communication strategies for duty-cycled sensor networks have been proposed [1], [2], [4], [5]. These solutions are often categorized into synchronous and asynchronous schemes. In the synchronous communication schemes [6], [7], all nodes wake up and sleep periodically according to a pre-defined common schedule. The disadvantage of this approach is that the data overhead due to pre-synchronization and overhearing may consume significant energy [4], [5]. In the asynchronous communication schemes, the nodes also wake up periodically, but not based on a common synchronized schedule [4], [8], [9]. A wake-up preamble, at least equal in length to one sleep-listen period of the receiver, is sent ahead of data. An important benefit is that the asynchronous schemes avoid the energy cost required to synchronize nodes. A drawback, however, is that the lack of synchronization between nodes and the periodic listening requires longer (higher energy) wake-up preambles. The latter issue is avoided by an approach proposed by the authors of [5], known as the X-MAC protocol. In this approach the transmitter replaces the long preamble with periodic short wake-up preambles. The X-MAC reduces the redundant energy consumption due to idle listening, overhearing and data overhead. However, the energy consumption of the nodes for periodic channel listening is still a substantial issue of WSNs. It is therefore of interest to study WSNs where nodes are equipped with low-power wake-up receivers (WRxs).

Low-power WRxs for WSNs have been discussed for about a decade [10], [11]. Early WRxs [11] were assumed to be always on and continuously listen to the channel, while the main receiver and transmitter are switched off. When a wake-up preamble is detected, the main radio is switched on for data reception. Low-power WRxs can be combined with periodic listening to achieve even lower energy consumption.

In this work we develop and analyze a duty-cycled medium access scheme for low-power WRxs, the DCW-MAC. We define a generic system where the nodes use low-power WRxs, for which we derive closed form expressions for total energy consumption per packet. These expressions are then used to optimize protocol parameters for lowest possible energy consumption, given certain hardware parameters. The main differences between this work and [10] are that we *i) take into account that ultra-low-power WRxs may come with a significant performance degradation* and *ii) analyze the total power consumption of an entire network with duty-cycled WRxs*. The model is provided for two different WRx scenarios: a) with receiver duty cycling, listening to the channel periodically, and b) when the WRx is always on and continuously monitors the channel, like in [11]. We compare these energy models with the energy models of a system where no low-power WRx is available and the main receiver is used for listening to the channel.

First we give a description of the overall operation of the addressed systems in Section II. The different states of the nodes (sleep, active, standby, off, etc.) and the interaction between them are described in detail. In Section III we present the analytical models of the average energy consumption per packet for different MAC schemes and for nodes with different hardware architectures. The analytical expressions are then used to determine the optimal protocol parameters (sleep-listen periods) in Section IV. Next, we evaluate the performance of the WRx-MAC protocols[1] and compare them for different traf-

[1]In this paper WRx-MAC refers to both the DCW-MAC and the always-on WRx-MAC.

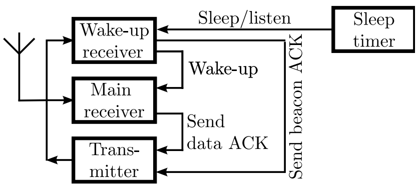
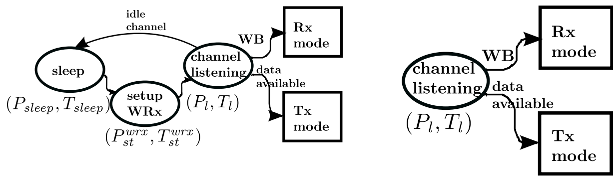


Fig. 1. Node architecture block diagram, with signaling in listen/receive mode shown.



(a) DCW-MAC scheme. (b) Always-on WRx MAC scheme.

Fig. 2. State-transition diagram of overall operation of a node for WRx-MAC schemes.

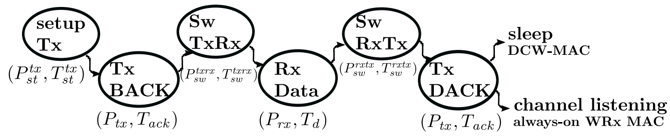


Fig. 3. Receiver state-space model.

fic conditions in Section V. Finally, conclusions and remarks are given in Section VI.

II. System description

A generic block diagram of the reference node architecture is shown in Fig. 1, where the node consists of a transmitter, a main receiver and a duty-cycled WRx. The WRx is switched on periodically by the sleep/listen timer and listens to the channel for any potential communication. The main receiver is switched on only when there is data to receive. Whenever the node has a packet to transmit, the transmitter is set up to send out periodic wake-up beacons (WBs) to the target receiver, similar to the X-MAC scheme. When the listen period of the WRx coincide with a WB transmission carrying its ID, it detects the beacon and transmits a beacon acknowledgement (BACK) message back. The transmitter node therefore has to change to the receive mode after each WB to investigate if a BACK is available. If a BACK is received, the node starts transmitting data, which is then acknowledged by the receiver (DACK). As long as no BACK is received, a node with data continuously repeats WB transmission.

In the always-on WRx MAC protocol, which we use as a reference, the WRx listens continuously to the channel and no listen/sleep timer is required. In this scenario, only one WB carrying the address of the target receiver need to be transmitted. After the target receiver detects the WB with its ID, similar to the DCW-MAC, it sends back a BACK message. In these scenarios, both the WB and the BACK carry the source and destination addresses. However, the WB is detected by a low performance (low-power) WRx, while BACK is received by the main radio of its counterpart. We take this performance loss into account as a WRx loss. Assuming that the WRx has a k[dB] higher noise figure than the main receiver, the WB needs to have k[dB] more energy than the BACK for equal detection performance. This is achieved in principally two different ways; *i) keeping WB time duration (same data rate) and increase the transmit power* or *ii) keeping the WB transmit power and making the duration longer (lower data rate)*. The first approach requires a large dynamic range of the transmitter, while the second increases the delay before a WB is detected. We have chosen to follow the second approach in this analysis.

A. Reference traffic scenario and assumptions

We consider a system of N nodes where all nodes have equal functionality and are able to directly communicate with each other. Furthermore, we assume that data packets to transmit, arrive according to an exponential distribution with parameter λ where each data packet transmission takes T_d seconds. This implies that the mean interval time between two packets is $1/\lambda$ seconds on average. Since we are interested in ultra-low power scenario, we also assume that packets are rare in the sense that $1/\lambda \gg T_d$. Under these assumptions we ignore any energy consumption resulting from side-effects of collisions in the transmission, allowing us to make tractable analytical derivations of optimal sleep and listen times for the analyzed protocols. We will also assume perfect detection of signals, whenever the targeted receiver is listening in the correct time interval.

B. State-space model

The overall operation of a single node accessing the medium for two different MAC scenarios is illustrated in Fig. 2. The sleep state in the DCW in Fig. 2(a) represents the node status when both the WRx and the main radio are switched off. The power consumption in this state is determined by the sleep/listen timer and the radio static power. In the channel-listening state the low power WRx is turned on to examine the channel. The parameters $(P_{state}^{part}, T_{state}^{part})$, shown below each state represent the power consumption of, and the time interval spent in, the corresponding state. With this notation, the energy consumed in a certain *part* of the receiver when in a certain *state* is $E_{state}^{part} = P_{state}^{part} T_{state}^{part}$.

The behavior of a node when acting as a transmitter or receiver is described in more detail by the state-space diagrams in Fig. 3 and Fig. 4. Switching between transmitting and receiving modes comes at a cost in both time delay and energy consumption, which are represented by the switching states **Sw TxRx** and **Sw RxTx**. Correspondingly, the transition to setup the main radio is modeled by the state **Setup Tx**. The node has the same behavior for the two MAC schemes in receiving mode, see Fig. 3. However, the node operates differently in the transmitter mode. When using the always-on WRx protocol, the transmitter needs to send only one WB to wake the target receiver. When using the duty-cycled WRx protocol the nodes communicate asynchronously and the transmitter sends the WB periodically until a BACK is received from the target node. This difference in the behavior of a node in Tx mode is depicted by the dashed lines in Fig. 4. The parameter N_{bmax} denotes the maximum number of periodic WB transmissions/BACK listening for a guaranteed success (given the perfect detection assumption).

III. Energy analysis

Based on the above, we present analytical models of the energy consumption for the addressed MAC schemes. For

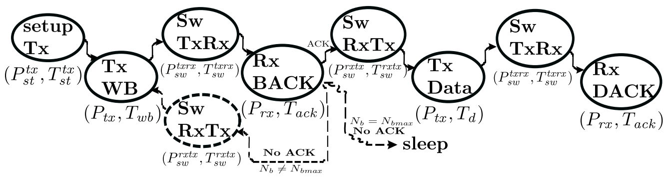


Fig. 4. Transmitter state-space model.

reference, we also compare these models to MAC protocols where nodes only consist of the main radio. The measure of energy consumption that we will use is the average energy consumption per packet, for an entire network of N nodes. In its simplest form, it is the sum of the transmitter, target receiver, and non-target receivers energy consumptions per transmitted packet. Denoting these E_{tx}, E_{rx}, and E_{nrx}, respectively, the average energy consumption per packet for N network nodes becomes

$$E = E_{tx} + E_{rx} + (N-2)E_{nrx}. \quad (1)$$

For notational convenience we assume that all nodes have a base-level power consumption, the sleep power P_{sleep} below which they cannot go. All other energy figures are in addition to this base-level. The base-level energy per received packet becomes P_{sleep}/λ, where P_{sleep} is the power consumption of the node in its sleep state. Furthermore, the switching energies as well as the switching times are all considered equal, *i.e.*, $E_{sw}^{txrx} = E_{sw}^{rxtx}$ and $T_{sw}^{txrx} = T_{sw}^{rxtx}$.

A. DCW-MAC

In the proposed DCW-MAC scheme, nodes always duty cycle unless data is available for transmission or the WRx has detected a WB. The communication between nodes is illustrated schematically for one packet arrival interval in Fig. 5, where **Node1** is the transmitter, **Node2** is the target receiver, and the other $N-2$ nodes are non-target receivers. Average energy consumption of the transmitter and receiver nodes, per packet, is given by

$$E_{tx} = \frac{P_{sleep}}{\lambda} + E_l^{tx} + E_{data}^{tx}, \text{and} \quad (2)$$

$$E_{rx} = \frac{P_{sleep}}{\lambda} + E_l^{rx} + E_{data}^{rx}, \quad (3)$$

respectively. The first term in these expressions is the base-level energy and the second term is the additional energy required for duty cycling, while the third term expresses the additional energy in Tx and Rx modes for the transmitter and receiver, respectively. The average energy consumption per packet for a non-target receiver is determined by the base-level energy consumption and the additional energy required for duty-cycling during one packet arrival interval, as

$$E_{nrx} = \frac{P_{sleep}}{\lambda} + E_l^{nrx}. \quad (4)$$

The transmitter and WRx communicate asynchronously, therefore the WRx needs to listen to the channel for at least a time-period $2\,T_{wb} + 2\,T_{sw}^{txrx} + T_{ack}$ to guarantee detection of a WB. Furthermore, when data is available for transmission, the transmitter sends the WB periodically and waits to receive a BACK after each one. At least one WB need to be transmitted to initiate communication and in the worst case, depicted in Fig. 5, the first WB is incompletely received by the target WRx and consequently WBs need to be transmitted until the next WRx listening period. This maximum number of WB

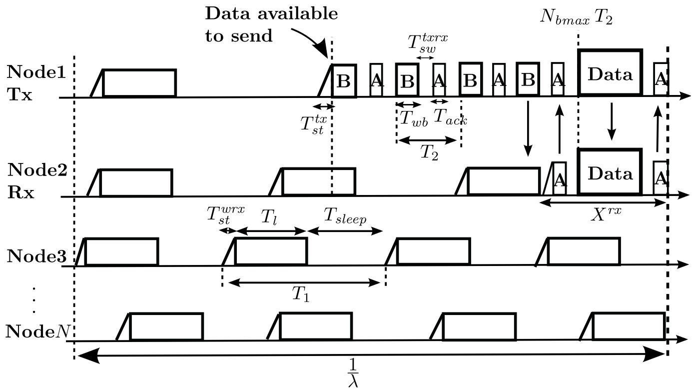


Fig. 5. DCW-MAC scheme.

transmissions is given by

$$N_{bmax} = \frac{T_1 + T_2}{T_2} = 1 + \frac{T_{sleep} + T_{st}^{wrx} + T_l}{T_l - T_{wb}}.$$

With asynchronous nodes, no number of transmitted WBs is more likely than any other and the average number of periodic WB-BACK periods per packet is

$$\bar{N}_b = \frac{N_{bmax} + 1}{2} = \frac{T_{sleep} + T_{st}^{wrx} + T_l}{2\,(T_l - T_{wb})} + 1.$$

The consumed energy in Tx mode, E_{data}^{tx} in (2), is the contribution of the energy of periodic WB-BACK as well as the energy of data transmission and is given by

$$E_{data}^{tx} = E_{st}^{tx} + \bar{N}_b\,E_{wb} + E_d, \quad (5)$$

where

$$E_{wb} = P_{tx}\,T_{wb} + P_{mrx}\,T_{ack} + 2\,E_{sw}^{txrx}, \text{and}$$
$$E_d = P_{tx}\,T_d + E_{sw}^{txrx} + P_{mrx}\,T_{ack}.$$

Using the state-space model, the average energy consumption in Rx mode, E_{data}^{rx} in (3), becomes

$$E_{data}^{rx} = E_{st}^{tx} + P_{tx}\,T_{ack} + P_{mrx}\,T_d + P_{tx}\,T_{ack} + 2\,E_{sw}^{txrx}. \quad (6)$$

Moreover, the channel listening energy, consumed by the transmitter, receiver, and non-target receiver, becomes

$$E_l^{part} = \bar{N}_l^{part}\,\left(E_{st}^{wrx} + P_{wrx}\,T_l\right), \quad (7)$$

where

$$\bar{N}_l^{part} = \frac{1/\lambda - X^{part}}{(T_{sleep} + T_{st}^{wrx} + T_l)}$$

denotes the average number of WRx duty-cycles in the interval where nodes are in idle mode. Above, *part* is either *tx*, *rx*, or *nrx*, and for notational convenience we introduced

$$X^{tx} = T_{st}^{tx} + \bar{N}_b\,T_2 + T_d + T_{sw}^{txrx} + T_{ack},$$
$$X^{rx} = T_{st}^{tx} + 2\,T_{ack} + 2\,T_{sw}^{txrx} + T_d, \text{and}$$
$$X^{nrx} = 0.$$

Replacing (6) and (7) back in (2)-(4) and (1) gives the energy consumption per packet.

B. Always-on WRx-MAC

The communication between nodes in the always-on WRx-MAC protocol, for one packet arrival interval, is illustrated in Fig. 6. As for the DCW, the average energy consumption of the transmitter, receiver and non-target receivers is modeled by (2)-(4), respectively. The two fundamental differences, as compared to the DCW case, are i) that the WRx now

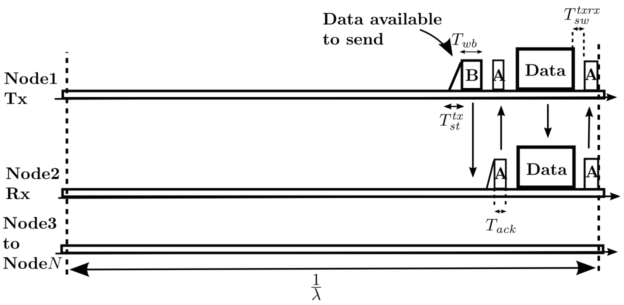


Fig. 6. Always on WRx-MAC scheme.

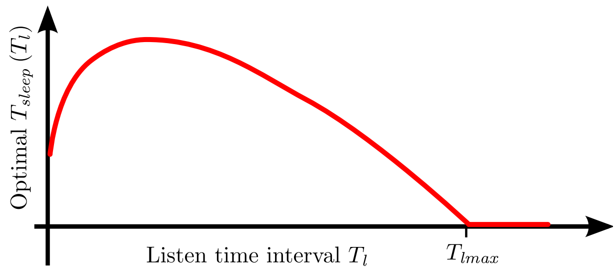


Fig. 7. Illustration of the optimal relationship between sleep and listen interval.

continuously monitors the channel, which changes (7) to

$$E_l^{part} = \frac{P_{wrx}}{\lambda}, \tag{8}$$

and ii) the transmitter only needs to send one WB to initiate communication, which changes (5) to

$$E_{data}^{tx} = E_{st}^{tx} + E_{wb} + E_d. \tag{9}$$

With these changes, the same procedure as for the DCW-MAC is used to calculate the energy per packet.

C. X-MAC

In the X-MAC, nodes consist of only the main radio, which duty-cycles and listens to the channel periodically [5]. The energy models of the transmitter, receiver and non-target receivers presented in Section III-A apply to this algorithm as well. In the energy models, however, the WRx power consumption, P_{wrx}, setup time, T_{st}^{wrx}, and setup energy, E_{st}^{wrx}, are replaced by P_{mrx}, T_{st}^{mrx} and E_{st}^{mrx}, respectively.

Furthermore, in this scenario both the ACK and WB are received by the full performance main receiver and therefore no increase in transmit energy for the WB is needed to compensate for the low performance of the WRx. This does not change the energy expressions, but the required transmission time T_{wb} for the WB will be reduced, as compared to the other cases.

IV. Optimal sleep intervals

To complete the design of the DCW-MAC protocol, we need to select the sleep-listen time intervals for given power consumptions in the different states, energies required for state transitions, and specific traffic conditions. The first step in this process is the observation that the WRx needs to listen during a time interval

$$T_l \geq 2\,T_{wb} + 2\,T_{sw}^{txrx} + T_{ack} \tag{10}$$

to guarantee that entire incoming WB will be caught. The second step is to select, for a given listen time T_l, a sleep time T_{sleep} which minimizes the total power consumption of the network. By differentiating (1) w.r.t. T_{sleep} and taking into account that the sleep time has to be non-negative, we obtain an optimal value of

$$T_{sleep}\left(T_l\right) = \max\left(\sqrt{\Gamma} - T_l - T_{st}^{wrx}, 0\right), \tag{11}$$

where

$$\Gamma = \frac{2\,\left(P_{wrx}\,T_l + E_{st}^{wrx}\right)}{\left(k\,P_{tx} + P_{mrx}\right)\,T_l + \left(2\,k+1\right)\,E_{sw}^{rxtx}} \cdot \left(\frac{N}{\lambda} - 2\,T_d - T_{st}^{tx} - 5\,T_{sw}^{txrx} + \frac{k+4}{2\,k+1}\,T_l\right) \cdot \left(\left(k+1\right)T_l + \left(2\,k+1\right)T_{sw}^{rxtx}\right).$$

Fig. 7 illustrates the relationship between listen and optimal sleep time intervals. We observe that for long listen times the best choice for the nodes is not to sleep at all, since $T_{sleep}\left(T_l\right) = 0$ for T_ls larger than some T_{lmax}.

The sleep time interval increases with power or energies related to the WRx and decreases with higher beacon transmit power. Furthermore, both the maximum listen time interval and the sleep time interval increase with higher average intervals between packets (lower packet arrival rate). The latter will introduce a long delay before initiating any data transmission since the transmitter must send periodic WB-ACKs until the target receiver wakes up and detects a WB. Moreover, an extra delay is introduced due to the poor performance of the WRx and transmission of the long WBs. In the worst case, the longest delay occurs when the first WB is incompletely received by the target WRx and WBs have to be transmitted until the next WRx listening period and is given by

$$D = T_{sleep} + \alpha\,T_l + A, \tag{12}$$

where $\alpha = (\frac{3}{2} + \frac{1}{2\,(2\,k+1)})$ and $A = T_{sw}^{txrx} + T_{st}^{tx} + T_{st}^{wrx}$.

If a receiver node is required to respond in a limited time period $D < D_{max}$, then from (12) the receiver sleep time is restricted to

$$T_{sleep}(D_{max}, T_l) < D_{max} - \alpha\,T_l - A \tag{13}$$

to meet the requirement of the system. However, to minimize the total energy consumption of the system the optimal value of T_{sleep} is selected by (11). Therefore, to fulfill the system requirement and to minimize the network total energy consumption for a given listen time T_l, the sleep time is selected as

$$T_{sleep} = max(0, min(T_{sleep}^{opt}, T_{sleep}^{dreq})), \tag{14}$$

where T_{sleep}^{opt} and T_{sleep}^{dreq} denote the optimal sleep time and the required sleep time to meet the delay requirement, respectively.

V. Results

In this section we evaluate the energy performance of the WRx-MAC schemes and compare it with the X-MAC. The radio characteristics and protocol parameters used to obtain the numerical results are listed in Table I. The parameters are based on initial estimates from the *Ultra-portable devices* project at the Department of Electrical and Information Technology, Lund University.

The lengths of the WB and ACK are chosen to be 20 bits. We also assume that the WRx has a 20 dB worse noise figure (NF) than the main radio. This is compensated by a WB which is $k = 100$ times longer in the WRx-MAC scenarios. For the X-MAC scenario, where the main receiver is used for receiving the WB, we set $k = 1$. Considering equality in (10), the listen intervals for the WRx-MAC and the X-MAC become 16.08

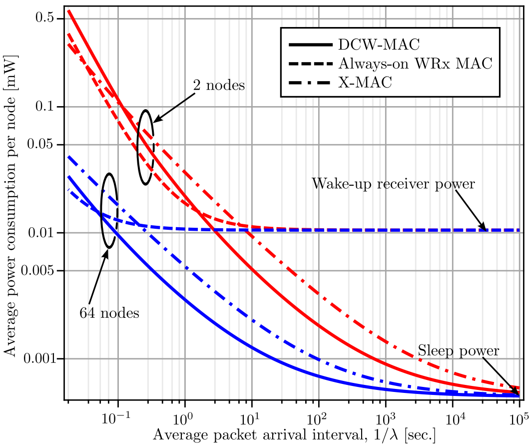


Fig. 8. Average power consumption per node vs. average packet arrival interval.

ms and 0.25 ms, respectively.

TABLE I
SYSTEM PARAMETERS.

(a) Radio characteristics.

Parameter	Value
P_{sleep}	$0.5\ \mu$W
P_{tx}	1 mW
P_{mrx}	1 mW
P_{wrx}	0.01 mW
$P_{st}^{tx} = P_{st}^{mrx}$	0.5 mW
P_{st}^{wrx}	0.01 mW
$P_{sw}^{txrx} = P_{sw}^{rxtx}$	1 mW
$T_{st}^{tx} = T_{st}^{mrx}$	1 ms
T_{st}^{wrx}	negligible
$T_{sw}^{txrx} = T_{sw}^{rxtx}$	$5\ \mu$s

(b) Protocol parameters.

Parameter	Value
T_{ack}	0.08 ms
T_{wb}	k (0.08) ms
T_d	2 ms
R_b	250 kbps

Let us start without delay requirements. Fig. 8 shows the node mean power consumption[2] of the DCW-MAC, always-on WRx-MAC and X-MAC, as a function of average packet-arrival intervals for two different network sizes and with optimal sleep intervals chosen according to (11). Two principal things are observed: i) for long average packet-arrival intervals (low traffic), the optimal sleep intervals of the DCW-MAC and the X-MAC increase and they result in the lowest power consumption; ii) for short average packet-arrival intervals (high traffic), the sleep mechanism gives less energy savings and the MAC schemes using the low-performance WRxs start to suffer from the high-energy WBs needed. The proposed DCW-MAC has the largest gain over the other schemes in the "mid-range" of packet-arrival intervals. Now, we consider the case where we have a maximum-delay requirement. Both the DCW-MAC and the X-MAC consume more power at long average packet-arrival intervals (low traffic), since their sleep periods now get restricted. This in contrast to the always-on WRx-MAC, where the nodes continuously monitor the channel. We illustrate the resulting power consumption, for a maximum delay requirement of 40 msec, in Fig. 9. The power performance of the DCW-MAC, always-on WRx-MAC and X-MAC are again compared for two different network sizes – this time with the sleep interval selected according to (14). The minimum power consumption of the X-MAC increases beyond the WRx power consumption and becomes inferior to the always-on WRx-MAC scheme. With increasing demands on maximum delay, the DCW-MAC minimum power consumption converges to the WRx power consumption, while

[2]Calculated as energy per packet per node per packet arrival time.

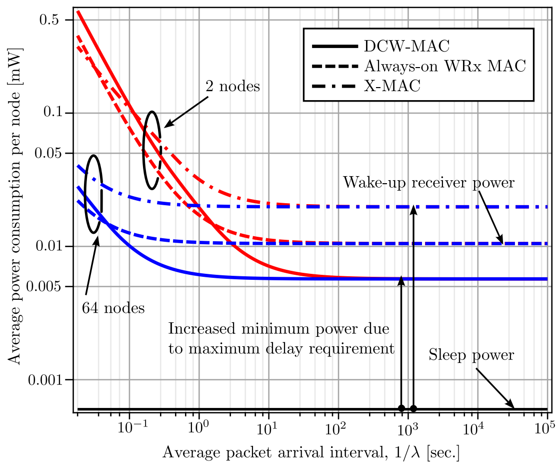


Fig. 9. Average power consumption per node vs. average packet arrival interval.

the X-MAC minimum power consumption converges to the (much higher) main receiver power. The proposed DCW-MAC now has clear gains over the other two MAC schemes, for all "long" packet-arrival intervals.

VI. CONCLUSIONS AND REMARKS

This paper presents a new medium access control scheme for WSNs, the DCW-MAC, which combines the energy saving mechanisms of duty-cycled medium access [5] and low-power wake-up radios [10]. An important part of the energy analysis is that we take the reduced detection performance of low-power WRxs into account in the analysis. The DCW-MAC is analyzed, energy optimized and compared with other MAC schemes. While the low performance of the WRx limits the performance of the DCW-MAC for high-traffic scenarios, it significantly outperforms other MAC schemes in low-traffic scenarios encountered in many low-power sensor networks.

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