Energy Efficient IR-UWB WBAN using a Generic Wake-up Radio based MAC Protocol

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ABSTRACT

This paper addresses the energy efficiency of impulse radio (IR-UWB) based wireless body area networks (WBAN). An energy efficiency optimization model is proposed for the IR-UWB WBAN which is based on a generic wake-up radio (WUR) based medium access control (GWR-MAC) protocol. GWR-MAC takes advantage of the WUR to decrease the network energy consumption especially in applications with rare events. Energy efficiency gains are enabled by using a dual-radio approach, in which a specific WUR is used to trigger the wake-up of main data radio. Proposed analytical energy efficiency model enables to compare the GWR-MAC based WBAN energy consumption with the duty cycle radio based approach. Results clearly show the GWR-MAC potential to improve the energy efficiency of IR-UWB based WBAN.

Categories and Subject Descriptors

C.2.2 [**Computer - Communication Networks**]: Network Protocols; C.2.1 [**Computer - Communication Networks**]: Network Architecture and Design—*Wireless Communication*

General Terms

Performance, Design, Reliability, Theory

Keywords

wireless body area network, impulse radio ultra wideband, medium access control, wake-up radio

UWBAN 2014, September 29-October 01, London, Great Britain

DOI 10.4108/icst.bodynets.2014.256968

1. INTRODUCTION

Energy efficiency of communication is highly important in wireless body are networks (WBAN), which have various application possibilities [4, 18]. The IEEE 802.15.6 standard defines physical (PHY) and medium access control (MAC) layer techniques, which have suitable modes for different type of WBAN scenarios [5]. One of the PHY layer options is impulse radio ultra wideband (IR-UWB), which has potential for very low-power communication. The MAC layer protocol for the IR-UWB based WBAN is defined to be slotted Aloha (S-Aloha) [1, 16], which is simple and suitable for applications which have low traffic load. The combination of IR-UWB PHY using non-coherent energy detection (ED) receiver and S-Aloha MAC is addressed in this paper.

For energy saving purposes it is important to keep the network node's radios in a sleep mode when they are not required to participate to communication. In most of the wireless sensor network (WSN) and WBAN MAC protocols the sleep / awake period's scheduling is managed by using duty cycle approach [12]. In such protocol's case, node's radios are waken-up to listen the channel, asynchronously or synchronously, to detect possible transmissions targeted for them, or to transmit their own data packets. In recent years, the wake-up radio (WUR) based approaches have gained attention among researchers [2, 9, 11, 13]. In that case the nodes have two radios: a wake-up radio and main data radio. The WUR is continuously on a very low power idle mode in which it is able to detect the wake-up signal (WUS). After WUS detection, the WUR awakes a micro-controller, which controls the main radio to take care of the data transmissions and receptions. WUR based approach enables immediate wake-up and low communication latency while in duty cycle approach the communication latency depends on the duty cycle. If the duty cycle is very low, energy will be saved but then the communication latency increases due to the radio's long sleep period length when nodes are not able to communicate. WUR based approaches have remarkable potential to enable very energy efficient solution especially in applications where events occur rarely. Therefore, in this paper the focus is on the evaluation of WUR approach energy efficiency in comparison to duty cycle based MAC (DCM) based approach.

In [7], it has been proposed a generic wake-up radio based MAC (GWR-MAC) protocol and an energy efficiency model, which enables GWR-MAC and DCM performance comparison for the narrowband PHY based WBAN case. Here the model proposed in [7], is revised to enable energy efficiency evaluation of IR-UWB based WBAN. In addition, the joint success probability for PHY and MAC layers are derived for additive white Gaussian noise (AWGN) case and taken into account in energy efficiency evaluation while in [7] a fixed bit error probability was assumed for the communication links.

2. SYSTEM MODEL

Here it will be described the topology and scenario assumptions of the WBAN which energy efficiency is under evaluation in this paper. In addition, the main features of communication protocols will be described and success probability derivations for the PHY and MAC layers are introduced.

2.1 Topology and scenario

A typical star-topology WBAN with N sensor nodes and a hub is assumed in this work as defined in [5]. The sensor information collected by the nodes will be send to the hub which can, depending on the application, take actions based on the information or forward it, for example, to a remote monitoring and control center (e.g., hospital). Here the focus is on the energy efficiency of communication between sensor nodes and the hub. It is assumed that sensor nodes will perform sensing and send the information to the hub, in a one-hop fashion, once it is required from the application point of view. For example, if the sensor value exceeds some predefined threshold, the sensor node must send the information to the hub.

2.2 Communication protocols

To enable energy efficient communication between the sensor nodes and hub, physical and MAC layers must be designed carefully. Here it will be described the assumed methods for wake-up management and PHY & MAC layer protocols, and their joint success probability is derived.

2.2.1 *Wake-up management*

It is important that all the node's power consuming components can be put to a sleep mode when they are not required. In WSNs and WBANs the sleep management is typically arranged by using a duty cycle based MAC protocols. In DCM protocols case, the node's radios follow a sleep / awake schedule, i.e., they wake-up to listen the channel or to transmit data. The frequency and duration of awake periods depends on the MAC protocols duty cycle parameter.

Other option for wake-up management is to use a dual radio approach composed of a specific wake-up radio and main data radio. WUR is continuously on a very low power idle mode in which is able to detect the wake-up signal. After WUS detection a wake-up of main radio is triggered via micro-controller unit (MCU) of the node.

In this paper a WUR based approach's energy efficiency is compared to the conventional DCM based approach. The

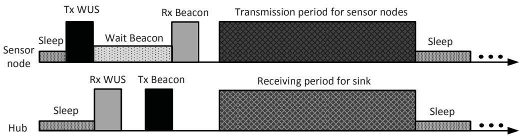

Figure 1: GWR-MAC protocol source-initiated mode.

DCM based approaches have been widely studied while WUR based approaches have gained attention recently. In the WUR based case, a GWR-MAC protocol proposed in [7] is assumed to be used. GWR-MAC protocol is based on dual-radio assumption, i.e., the WBAN nodes have a specific WUR and main data radio. GWR-MAC defines a source-initiated and sink-initiated wake-up procedures which are followed by a transmission / receiving period dedicated for the data communication. GWR-MAC is not restricted to any specific WUR technology or data radio technology. The data transmission / receiving period can be implemented by using different types of medium access control methods depending on the application requirements. Therefore, GWR-MAC protocol design enables scalability to different application scenarios. Here it is assumed that the source-initiated mode of GWR-MAC, illustrated in Figure 1, is used since in the target scenario the data flow is from the sensor nodes to the hub. In this case the sensor node(s) is assumed to wake-up the hub from the sleep mode once there is data to transmit to the sink. Sink node will receive the WUS and then send a beacon which includes information about the following transmission period. Here will be assumed that slotted Aloha channel access will be used during the transmission period.

2.2.2 *IR-UWB PHY and S-Aloha MAC*

For the data communication, the IR-UWB physical layer with ED receiver is used in this work. Further it is assumed, that on-off keying (OOK) modulation combined with waveform coding is used as defined for the mandatory mode of the IEEE 802.15.6 standard [5]. Therefore, the IR-UWB symbol time is divided into two intervals of duration $T_{\text{sym}}/2$. Symbol structure enables also time hopping positions $(N_{\text{w}}/2-1)$ in order to support multi-BANs for coexistence. The waveform coding maps K information bits onto coded-pulse sequences of length $2K$ from an alphabet of size $M = 2^K$ [5]. According to the standard, in the mandatory mode $K = 1$ $(M = 2)$ and optional mode shall use $K = 4$ $(M = 16)$. Due to waveform coding and half-rate mapper, the symbol time coincides with the binary pulse position modulation (BPPM) symbol time for all M.

IR-UWB signal is based on pulse waveforms of duration $T_{\text{w}} = N_{\text{cpb}}T_{\text{p}}$, where $N_{\text{cpb}} \geq 1$ is the number of pulses per burst and T_{p} is the pulse duration [5]. I.e., the pulse waveform, T_{w}, can be formed using a single pulse or multiple pulses.

The pulse shaping will place a pulse waveform according to the IR-UWB symbol structure when the input bit is one. Therefore, the OOK modulated signal for the m:th symbol can be expressed as [5]

$$x^m(t) = \sum_{n=0}^{2K-1} d_n^m \times \\ w_{2Km+n}(t - n(T_{\text{sym}}/2) - mKT_{\text{sym}} - h^{(2Km+n)}T_{\text{w}}), \quad (1)$$

where $m \geq 0$, d_n^m is the n:th waveform coding component over the m:th symbol, T_{sym} is the symbol time, $h^{(2Km+n)}$ is the time hopping sequence and $w(t) = \sum_{i=0}^{N_{\text{cpb}}-1} p(t - iT_{\text{p}})$, assuming that scrambling is not used. The uncoded data rate for OOK modulation can be calculated as $R = 1/T_{\text{sym}}$. The scrambling and time hopping does not affect to the bit error probability (BEP) derivation of interference free AWGN channel used hereafter, therefore they will be ignored for simplicity. In the OOK case with 2-ary waveform coding the transmitted signal for the m:th bit is defined as

$$s^m(t) = d_0^m \times \\ \sum_{i=0}^{N_{\text{cpb}}-1} \sqrt{\frac{E_{\text{b}}}{N_{\text{cpb}}T_{\text{p}}}} p(t - mKT_{\text{sym}} - iT_{\text{p}}) \\ + d_1^m \times \\ \sum_{i=0}^{N_{\text{cpb}}-1} \sqrt{\frac{E_{\text{b}}}{N_{\text{cpb}}T_{\text{p}}}} p(t - (T_{\text{sym}}/2) - mKT_{\text{sym}} - iT_{\text{p}}), \quad (2)$$

where E_{b} is the energy per bit in binary modulation case.

A non-coherent ED receiver operation principle is that after the antenna, the signal goes through a band-pass filter, which eliminates the out-of-band noise. Then a square law operation is performed to the filtered signal and the integrator is used to capture the signal energy and additional noise. In the OOK combined with 2-ary waveform coding case, the symbol decision can be done by comparing the amount of received energy of symbol intervals in order to determine whether the transmitted bit was one or zero. Theoretical BEP in the AWGN case can be then calculated by using the approach introduced for ED receiver with BPPM in [15]. Therefore, SNR at the decision variable of ED receiver is calculated as [15]

$$SNR_{\text{DV}} = \frac{2\frac{E_{\text{b}}^{\text{I}}}{N_0}}{4 + N_{\text{cpb}}2TW\frac{N_0}{E_{\text{b}}^{\text{I}}}}, \quad (3)$$

where T is the integration time per pulse, W is the signal bandwidth and E_{b}^{I} is the integrated energy per bit. By assuming Gaussian approximation, BEP can be calculated by using (3) and the $Q(\cdot)$ function [15].

The IEEE 802.15.6 standard defines that the Bose-Chaudhuri-Hocquenghem (BCH) code with parameters $n = 63, k = 51$ and $t = 2$ shall be used in the default mode for forward error correction (FEC). It must be taken into account that in the coded case, the energy per transmitted bit will be less than in the uncoded case. Therefore, the energy per bit for the BCH code rate is $E_{\text{c}} = rE_{\text{b}}$, where $r = k/n$ is the code rate [10],[14]. That assumption will enable that transmitted packet will contain the same amount of bit energy in uncoded and coded case. Therefore, the bit error probability before decoding (before correcting the errors) can be calculated as [14]

$$P_{\text{bd}} = Q\left(\sqrt{SNR_{\text{DV}}^{\text{c}}}\right), \quad (4)$$

where $SNR_{\text{DV}}^{\text{c}}$ is the signal-to-noise ratio at the decision variable for BCH coded case. At the FEC decoder of the receiver, t bit errors can be corrected and the code word error probability for block codes of the form (n, k, t) can be calculated as [10],[14]

$$P_{\text{cw}} = \sum_{h=t+1}^{n} \binom{n}{h} P_{\text{bd}}^h (1 - P_{\text{bd}})^{n-h}. \quad (5)$$

The bit error probability for the used BCH code can then be approximated as [14]

$$P_{\text{b}} = \frac{1}{n} P_{cw} = \frac{1}{n} \sum_{h=t+1}^{n} \binom{n}{h} P_{\text{bd}}^h (1 - P_{\text{bd}})^{n-h}. \quad (6)$$

The packet error probability can be calculated as

$$P_{\text{Pa}} = 1 - (1 - P_{\text{b}})^l, \quad (7)$$

where l is the length of the packet in bits. Therefore, the physical layer success probability for a packet transmission and reception over a wireless channel can be calculated as

$$P_{\text{succ}}^{\text{PHY}} = 1 - P_{\text{Pa}}. \quad (8)$$

It must be taken into account that packet length increases due to parity bits of BCH coding. For certain packet lengths there may be also need for bit filling in order to align with the number of information bits (k) required in the last code word encoding. In this work the bit filling is taken into account as defined in the standard [5] and introduced also in [6].

In this work the channel access success probability needs to be also taken into account because the energy efficiency of wireless communication depends on both PHY and MAC layer success probabilities. In slotted Aloha case the random access period is divided into slots in which the nodes shall transmit their frames if they decide to transmit. Node transmission probability in a given slot depends on the channel contention probability, p. As was defined in Section 2.2.1, the hub shall transmit a beacon message at the beginning of the transmission period so that the nodes know when they should compete for channel access.

The MAC layer packet success probability for S-Aloha case can be calculated as

$$P_{\text{succ}}^{\text{MAC}} = Np(1 - p)^{N-1}, \quad (9)$$

where N is the number of nodes competing for the channel and p is the probability for a node to transmit in a slot. In order to achieve maximum success probability in the S-Aloha case, the offered traffic load must be $G = 1$, which corresponds to $p = 1/N$ for all nodes. In this work, it has been assumed that the channel competition probability optimizes the offered traffic load in the network, i.e., the results are given for the S-Aloha best case scenario. In that case, there is, in average, exactly one packet per slot to be transmitted. The joint success probability for the PHY and MAC layers can be calculated as

$$\gamma = P_{\text{succ}}^{\text{PHY}} P_{\text{succ}}^{\text{MAC}}, \quad (10)$$

which will be used in the next section to derive the average number of transmission required for successful packet transmission.

3. ENERGY CONSUMPTION MODEL

An energy consumption model, will be introduced in this section to enable comparison of the GWR-MAC and conventional DCM approach. The proposed model takes into account the energy consumption of sensing, processing and communications of both type of networks. The dominating energy consumption factors, of each transceiver's component, are taken into account: wake-up signaling, data transmission and reception, and MCU and sensor active mode current consumption. The relevant energy consumption characteristic, affecting the GWR-MAC and DCM approaches, are then addressed.

The total energy consumption during the network operation time, t, as a function of number of events and bit error probability for GWR-MAC based network's sensor nodes (SN) and hub (H), in the source-initiated case can be calculated as

$$\begin{aligned} &E^{\mathrm{SN}}_{\mathrm{GWR\text{-}MAC}}(\epsilon,t,\gamma) = E^{\mathrm{SN}}_{\mathrm{s}}(t) + E^{\mathrm{SN}}_{\mathrm{MCU}}(\epsilon,t) \\ &+ E_{\mathrm{TX,WUS}}(\epsilon,t,\gamma) + E_{\mathrm{wait,BC}}(\epsilon,t) + E_{\mathrm{RX,BC}}(\epsilon,t) \\ &+ E_{\mathrm{C}}(t) + E^{\mathrm{SN}}_{\mathrm{TX,D}}(\epsilon,t,\gamma) + E_{\mathrm{RX,ACK}}(\epsilon,t,\gamma) + E_{\mathrm{clk}}(t) \\ &E^{\mathrm{H}}_{\mathrm{GWR\text{-}MAC}}(\epsilon,t,\gamma) = E^{\mathrm{H}}_{\mathrm{s}}(t) + E^{\mathrm{H}}_{\mathrm{MCU}}(\epsilon,t) \\ &+ E_{\mathrm{TX,BC}}(\epsilon,t) + E_{\mathrm{RX,WUS}}(\epsilon,t,\gamma) + E_{\mathrm{C}}(t) \\ &+ E_{\mathrm{clk}}(t) + E^{H}_{\mathrm{RX,D}}(\epsilon,t,\gamma) + E_{\mathrm{TX,ACK}}(\epsilon,t,\gamma), \end{aligned} \tag{11}$$

where ϵ is the number of events during the operation time t, γ is the joint success probability of the PHY & MAC layers, $E_{\mathrm{TX,WUS}}$ and $E_{\mathrm{RX,WUS}}$ are the energy consumptions of WUS transmissions and reception, respectively. $E_{\mathrm{TX,BC}}$, $E_{\mathrm{wait,BC}}$ and $E_{\mathrm{RX,BC}}$ are the energy consumptions of BC transmission, waiting and reception, respectively. E_{C} is the constant energy consumption of the WUR and E_{clk} is the energy consumption of the clock needed to maintain the time synchronization. E^{x}_{s} is the energy consumption of sensing, E^{x}_{MCU} is the energy consumption of the MCU, $E^{x}_{\mathrm{TX,D}}$ and $E^{x}_{\mathrm{RX,D}}$ are the energy consumption of data transmissions and receptions, respectively, calculated separately for x is SN or H.

The total energy consumption during, t, as a function of number of events, duty cycle percentage and PHY & MAC joint success probability for DCM based network sensor nodes and hub in the source-initiated case can be calculated as

$$\begin{aligned} &E^{\mathrm{SN}}_{\mathrm{DCM}}(\epsilon,\lambda,t,\gamma) = E^{\mathrm{SN}}_{\mathrm{s}}(t) + E^{\mathrm{SN}}_{\mathrm{MCU}}(\epsilon,t) \\ &+ E^{\mathrm{SN}}_{\mathrm{RX,DC}}(\lambda,t) + E_{\mathrm{clk}}(t) + E^{\mathrm{SN}}_{\mathrm{TX,DE}}(\epsilon,t,\gamma) \\ &+ E^{\mathrm{SN}}_{\mathrm{RX,BC}}(\epsilon,t,\gamma) + E^{\mathrm{SN}}_{\mathrm{TX,D}}(\epsilon,t,\gamma) + E_{\mathrm{RX,ACK}}(\epsilon,t,\gamma) \\ &E^{\mathrm{H}}_{\mathrm{DCM}}(\epsilon,\lambda,t,\gamma) = E^{\mathrm{H}}_{\mathrm{s}}(\epsilon,t) + E^{\mathrm{H}}_{\mathrm{MCU}}(\epsilon,t) \\ &+ E^{\mathrm{H}}_{\mathrm{RX,DC}}(\lambda,t) + E_{\mathrm{clk}}(t) + E^{\mathrm{H}}_{\mathrm{RX,DE}}(\epsilon,t,\gamma) \\ &+ E^{\mathrm{H}}_{\mathrm{TX,BC}}(\epsilon,t,\gamma) + E^{\mathrm{H}}_{\mathrm{RX,D}}(\epsilon,t,\gamma) + E_{\mathrm{TX,ACK}}(\epsilon,t,\gamma), \end{aligned} \tag{12}$$

where λ is the duty cycle percentage, $E^{x}_{\mathrm{RX,DC}}$ is the energy consumption of channel listening according the duty cycle, $E^{x}_{\mathrm{TX,DE}}$ and $E^{x}_{\mathrm{RX,DE}}$ are the energy consumptions of detected event (DE) message transmission and reception, respectively, when x is SN or H. Here it is assumed that in the DCM approach case, the sensor node will send DE message if it has data to send for the hub. Depending on the channel access protocol, the DE message can be replaced, e.g., by using a preamble before the data packet. In the GWR-MAC network, $\lambda = 1$ (100%), because it is continuously listening the channel. In DCM based network, $0 < \lambda \leq 1$.

The duration of each mode (sensing, MCU active, transmit and receive different type of packets) must be known in order to calculate the consumed energy. They can be calculated as a function of the analyzed operation duration, t, and the number of events, ϵ, when the data rate R and length of the packets are known. In the WUR case the receiver is always ready to receive the WUS. Therefore, there is a constant receiver energy consumption component, E_{C}, for the whole duration of a network operation. In the DCM case, the receiver goes on and off according to duty cycle to listen the channel for possible oncoming transmissions. Therefore, the duty cycled receiver channel listening duration is a function of duty cycle λ.

The data packet, DE and WUS transmission times must be multiplied with the number of retransmissions required for successful detection. The packet error probability depends on the PHY and MAC layer success probabilities. The average number of transmissions required for success, n_{TX}, can be calculated by using Eq. (10) as $n_{\mathrm{TX}} = \frac{1}{\gamma}$.

The total energy consumption in the network (during t) can be calculated as

$$E(\epsilon,\lambda,t,\gamma) = N^{\mathrm{SN}} E^{\mathrm{SN}}_{z}(\epsilon,\lambda,t,\gamma) + N^{\mathrm{H}} E^{\mathrm{H}}_{z}(\epsilon,\lambda,t,\gamma), \tag{13}$$

where N^{SN} and N^{H} are number of sensor nodes and sink nodes, respectively, and z is GWR-MAC or DCM.

The energy consumption per event, E_{ϵ}, and normalized energy efficiency, η, can be calculated by using the definitions introduced in [8] as

$$E_{\epsilon}(\epsilon,\lambda,t,\gamma) = \frac{E(\epsilon,\lambda,t,\gamma)}{\epsilon} \tag{14}$$

and

$$\eta(\epsilon,\lambda,t,\gamma) = \frac{\min(E(\epsilon,\Lambda,t,\gamma))}{E(\epsilon,\lambda,t,\gamma)}, \tag{15}$$

where the minimum is calculated over the duty cycle value set $\Lambda = (0, 1]$ for each ϵ, t and γ combination. That minimum value is divided by the energy consumption per event for particular ϵ, λ, t and γ combination. Therefore, the metric defined in Eq. (15) will lead maximum energy efficiency to be one and enable a clear comparison for GWR-MAC and DCM approaches as a function of number of events, duty cycle percentage and joint success probability of PHY & MAC layers.

The proposed energy consumption model can be used to evaluate the energy consumption per event and normalized energy efficiency for different parameter setting and channel conditions. In order to enable straightforward performance comparison, here is defined a percentage improvement equation of energy consumption reduction per event as

$$E_{\mathrm{saving}} = 100\left(1 - \frac{E^{\mathrm{Alt}}_{\epsilon}(\epsilon,\lambda_{Alt},t,\gamma)}{E^{\mathrm{Ref}}_{\epsilon}(\epsilon,\lambda_{Ref},t,\gamma)}\right), \tag{16}$$

Table 1: Parameters for energy efficiency comparison

Parameter	Description	Value
N_{SN}	Number of sensor nodes	10
N_{H}	Number of hub nodes	1
$I_{TX,SN}$	TX mode current consumption in sensor node	18.5 mA
$I_{RX,SN}$	RX mode current consumption in sensor node	22.5 mA
$I_{RX,H}$	RX mode current consumption in hub node	22.5 mA
$I_{RX,DC}$	Current consumption of channel listening	22.5 mA
U	Operating voltage	3.0 V
$I_{C,WUR}$	WUR idle mode current consumption	12 µA
$I_{TX,WUR}$	WUS transmission current consumption	14.2 mA
$I_{RX,WUR}$	WUR RX mode current consumption	200 µA
I_{clk}	Clock current consumption	2 µA
R_{W}	WUR data rate	20 kbps
R_{SN}	Data rate, sensor node data radio	487 kbps
ϵ	Number of events per year	1 - 1000000
λ	Duty cycle percentage	0.1 - 5 %
$T_{s,H}$	Sensing time per event in hub node	15 s
$I_{MCU,SN}$	MCU current consumption in sensor node	1 mA
$I_{MCU,H}$	MCU current consumption in hub node	30 mA
$I_{s,SN}$	Sensor current consumption in sensor node	3 µA
$I_{s,H}$	Sensor current consumption in hub node	30 mA
L_{X}	Length of message, X = DE, ACK or BC	12 oct
L_{W}	Length of wake-up signal	20 oct
$L_{D,SN}$	Length of data packet	255 oct
$t_{wait,BC}$	Beacon waiting time	3.2 ms
t	Operation duration	one year

where $E_{\epsilon}^{\mathrm{Ref}}$ and $E_{\epsilon}^{\mathrm{Alt}}$ are the energy consumption per event for the reference case and for the alternative case considered for possible energy savings, respectively. λ_{Alt} and λ_{Ref} are the duty cycle for alternative and reference case, respectively.

4. RESULTS

The proposed energy consumption model has been implemented by using Matlab software and results are shown here. The parameters for GWR-MAC and DCM approach energy efficiency comparison are shown in Table 1. These parameters are approximated from the state of the art designs [3, 17, 19, 20] and from the IEEE 802.15.6 standard [5] definitions.

Figure 2 shows the network energy consumption (Eq. (13)) comparison for GWR-MAC and DCM based networks as function of E_b/N_0 and duty cycle percentage when the number of events per hour is two. It can be observed that GWR-MAC network consumes remarkably less energy than the DCM approach with duty cycle values $\lambda \geq 1\%$. DCM approach with lowest duty cycle (0.1 %) achieves almost as low energy consumption as GWR-MAC approach. However, so low duty cycle values are not practical because strict synchronization would be required and communication delay becomes a problem in applications which have low latency requirements. Figure 2 shows also the trend of the energy consumption increment of DCM network when the duty cycle increases. Moreover, this figure shows that the energy consumption of GWR-MAC and DCM approach starts to be the same when the E_b/N_0 decreases. When the E_b/N_0 is low, the number of data packet retransmission increases and the energy consumption of data transmissions starts to dominate over the wake-up mechanism energy consumption. Therefore, the GWR-MAC and DCM approaches' energy consumption is close to each other in difficult channel conditions combined with channel access success probability.

Figure 3 shows the energy consumption per event (Eq. (14)) as a function of number of events per year when E_b/N_0 is 13.58 dB. It can be observed that in comparison to typical low-power network duty cycle value $\lambda = 1\%$, the GWR-

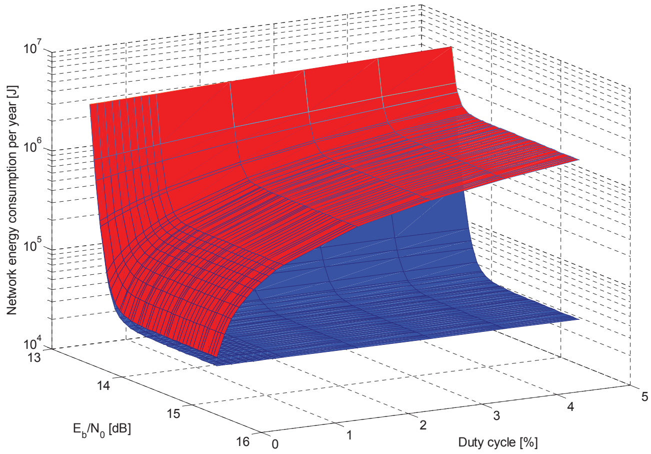

Figure 2: Total energy consumption comparison for GWR-MAC (blue) and DCM (red) approaches, two events per hour.

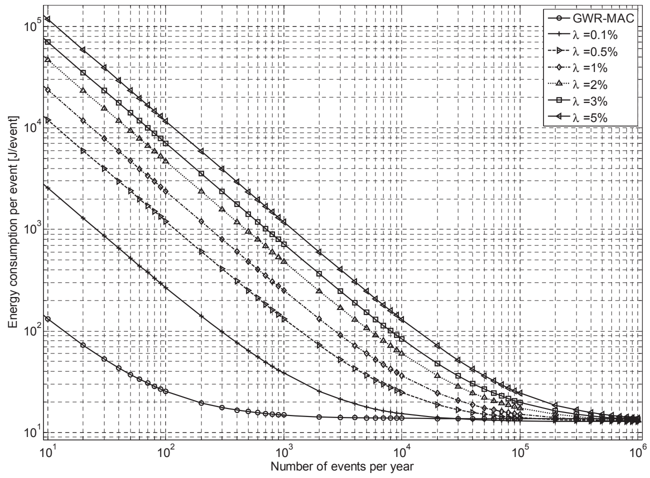

Figure 3: Energy consumption per event comparison for GWR-MAC and DCM approaches, E_b/N_0 = 13.58 dB.

MAC energy consumption is around too orders of magnitude lower when the number of events per year is 100. When the number of events per year is larger than $2 * 10^5$, the DCM approach with $\lambda = 1\%$ consumes less energy than GWR-MAC approach.

Figure 4 shows the energy efficiency (Eq. (15)) comparison as a function of number of events per year when E_b/N_0 = 15.26 dB. It can be observed that the GWR-MAC approach outperform also the lowest duty cycle case until the number of events increase to three per hour. In comparison to more practical duty cycle setting (1 %), the GWR-MAC network is more energy efficient until the number of events increases to 30 per hour.

Figure 5 shows the energy consumption per event saving percentage (Eq. (16)) as a function of number of events

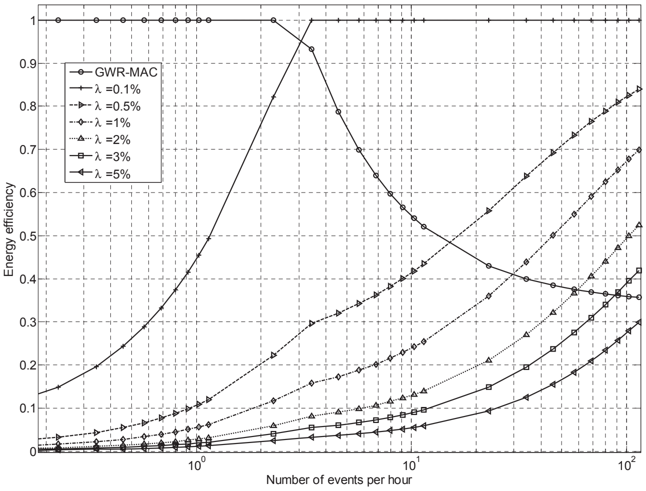

Figure 4: Energy efficiency of GWR-MAC versus DCM network, $E_b/N_0 = 15.26$ dB.

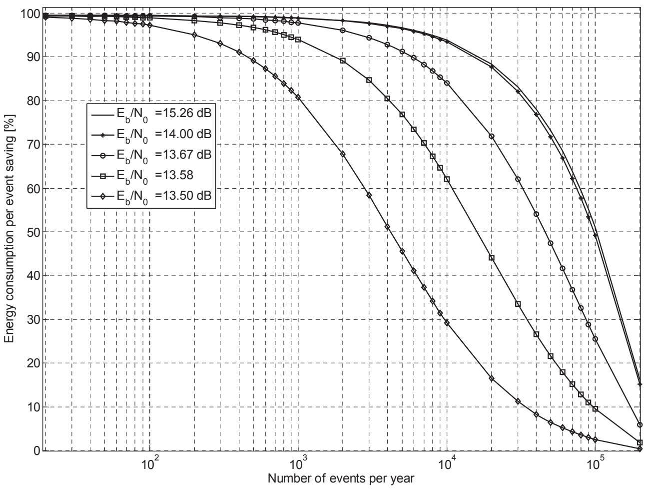

Figure 5: Energy consumption per event saving percentage of GWR-MAC versus DCM network.

per year for different E_b/N_0 values, when the alternative case is GWR-MAC and reference case is DCM with 1 % duty cycle. This result illustrates that when the number of events is low, the GWR-MAC energy saving percentage is 99 %. Figure 5 illustrates clearly that when the E_b/N_0 is high, more energy is saved because then the wake-up mechanism effect to the overall energy consumption is proportionally larger than in low E_b/N_0 case, because then the data packet retransmissions effect to the energy consumption increases.

5. CONCLUSIONS

In this paper was proposed an energy consumption model for IR-UWB based WBAN to enable comparison of a generic wake-up radio based medium access control approach and conventional duty cycle MAC based approach. Various energy consumption related metrics were defined for straightforward performance evaluation in AWGN case when taking into account joint success probability of IR-UWB PHY using non-coherent ED receiver and S-Aloha MAC which are selected methods for IEEE 802.15.6 standard based WBAN. The proposed model can be used to make selection between WUR and DCM based MAC solution as a function of number of events, duty cycle percentage and channel conditions. Results clearly showed that GWR-MAC network has remarkably lower energy consumption that DCM based network especially when the event frequency is low.

6. ACKNOWLEDGMENTS

The work has been partially funded by Academy of Finland by the project Dependable Wireless Healthcare Networks for Reliable Body Area Network-based Healthcare (DWHN) and by Finnish Funding Agency for Innovation (Tekes) through Enabling Future Wireless Healthcare System (EWiHS) project.

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