Energy Efficient UWB-WUR Dual-radio Solution for WBANs

Heikki Karvonen, Juha Petäjäjärvi, Ville Niemelä,
Matti Hämäläinen and Jari Iinatti
Centre for Wireless Communications
University of Oulu
Erkki Koiso-Kanttilan katu 3, 90570 Oulu, Finland
firstname.lastname@ee.oulu.fi

Ryuji Kohno
Medical ICT Center, Center of Medical Information
and Communication Technology
Yokohama National University
79-7 Tokiwadai, Hodogaya-ku, Yokohama, 240-8501 Japan
kohno@ynu.ac.jp

***Abstract*— A dual-radio solution for wireless body area networks (WBANs) is proposed in this paper. Solution is based on the usage of wake-up receiver (WUR) and impulse radio ultra wideband (IR-UWB) technique. In the proposition, the data to the hub is transmitted using IR-UWB and the control messages back to a node are received using WUR. Energy efficiency model has been developed to compare proposed solution's performance to a conventional duty-cycling based single radio solution. WUR design includes trade-offs between data rate, sensitivity and power consumption that are also explored in this work. Results show that the proposed solution can improve energy efficiency in WBANs which have asymmetric traffic between the sensor nodes and hub in the uplink and downlink direction.**

Keywords—energy efficiency; medical device; wake-up receiver; impulse radio ultra wideband (IR-UWB); wireless body area network;

I. Introduction

Wake-up receiver (WUR) based networking has a huge potential to improve energy efficiency in comparison to duty-cycling based approaches since the idle listening of channel leads to a redundant energy consumption [1]-[5]. In addition, the WUR based solution will decrease the amount of electromagnetic radiation of surrounding environment since the communication occurs only when necessary. Generally, the amount of wireless communication devices is increasing constantly. Therefore, it is important to minimize the electromagnetic radiation, especially in medical wireless body area networks (WBANs) communicating inside and around human body. Transceiver's radiation must be minimized also because the devices will create multi-user interference, making the wireless communication more challenging.

Here the focus is on a WBAN composed of on-body and / or implanted medical devices which can enable useful medical applications. One example of a useful WBAN application is a deployment of a node, which includes a sensor(s), a microcontroller unit (MCU), a wireless transceiver, doses of drugs and a power source. This kind of a device would be capable of performing a long-term automated medicine delivery taking into account perhaps varying physical condition of a patient. Devices must be able to send measured values and the amount of diffused medicine dosage outside the body for a controller node. The devices should also be manageable and reconfigurable wirelessly. The proposed solution has remarkable market potential since it could be used, e.g., to make long-term dosing easier for patient suffering from diseases such as diabetes, osteoporosis, multiple sclerosis and pain management. Automatic and adaptive dosing would make drug usage more precise, effective and it would improve compliance especially for patients that have difficulties to follow the dosage schedule (e.g. elderly or psychiatric patients). It is evident that the mentioned applications would be very valuable by saving human lives and society's money and would improve the quality of life of humans suffering from certain decease which require medicine. It is also clear that these applications have many challenges, from the medical and technical point of view. However, a solution developed by Microchips [6] shows that it is possible to deploy implanted microchip which contains 100's of medicine dosages that can be released to patient's body, and in [7] has been done a clinical study for an implantable continuous glucose monitoring (CGM) which can have a lifetime of 180 days.

In WBAN applications, there is a need for communication solutions for data transmission from inside the body to outside body receiver (medical implant communication service (MICS)) as well as communication on-body to on-body and to off-body by using, e.g., IEEE Std. 802.15.6 [8] techniques. In the implanted WBAN node case, the maximum allowed transmission power in 402 - 405 MHz MICS band is 25 µW, which sets tight requirements for the WUR sensitivity. Communication's reliability must also be very high since human's health would be in a danger due to a communication failure. Communication channel inside, and around, the human body is also very challenging. In the envisaged applications the nodes lifetime must be sufficiently long in order to enable user friendliness and usefulness of the application.

In this work, a combination of WUR and impulse-radio ultra wideband (IR-UWB) transmitter-only communication (UWB-WUR) solution is proposed for WBANs in order to fulfil strict energy efficiency requirement. This solution will enable the sensor node to send data using UWB technique while the control channel from hub to sensor node will be enabled by implementing the WUR. Typically, the WUR is used only for wake-up purpose but here it is proposed to be used also for receiving control messages. Control channel has typically less traffic and therefore the WUR usage will reduce unnecessary idle listening of the sensor nodes. Solution can be useful also in other types of short-range network applications, e.g., in vehicles, home and industrial scenarios. Energy consumption model is developed to explore proposed solution energy efficiency as well as to illustrate WUR design tradeoffs related to required sensitivity, data rate and power consumption.

II. Related Work

One of the most important ways to decrease energy consumption of the sensor node is to keep it in the sleep mode as much as possible. In a typical sensor node's radio, the medium access control (MAC) protocol takes care of the sleep / awake scheduling, i.e., duty cycling of the radios. There is a large amount of different type of duty-cycling based MAC protocols proposed for wireless sensor networks (WSNs) and WBANs. From the energy efficiency point of view, the drawback of duty-cycling is the unnecessary channel listening of the nodes when there are no incoming transmissions. If communication occurs rarely, the duty-cycle percentage must be set to be very small (< 1%) in order to avoid idle listening as much as possible. In this case the drawback is that the communication delay will increase since nodes are in the sleep mode for long periods of time. During the few recent years, WUR development has gained attention [13]-[19]. WUR can be continuously in an ultra-low-power idle mode and be able to detect wake-up signal (WUS) with very low power consumption. Typically a dual-radio approach is used to deploy sensor nodes which are equipped with WUR and data radio. Data radio can be continuously on a sleep mode and WUR will wake-up the data radio via the MCU once the WUS is detected. That enables to develop new type of WUR based MAC solutions for WSNs and WBANs in order to improve energy efficiency and decrease communication latency when changing from sleep mode to transmit mode [1] - [5]. For example a WUR based MAC protocol (a Generic Wake-up Radio based Medium Access Control (GWR-MAC) [1]) can be used as a starting point for communication design for the target WBAN applications.

Usually in WBAN applications the traffic load is asymmetric in uplink and downlink. In those applications it is more efficient to use higher data rate communication for uplink transmission and low data rate communication for downlink. UWB technology has been found to be a good candidate for WBANs and also standards have been published recently [8], [9]. There are previous works that propose to use UWB in a transmit-only mode due to relatively high energy consumption of an UWB receiver [10], [11]. However, there are not standardized solutions that take advantage of the WUR usage. Furthermore, according to authors' best knowledge, the WUR and UWB transmit-only combination has not been proposed earlier for WBANs.

III. System Model

The WBAN architecture and its connection to an external network is illustrated in Figure 1. Depending on the application, WBAN can include one or multiple sensor nodes

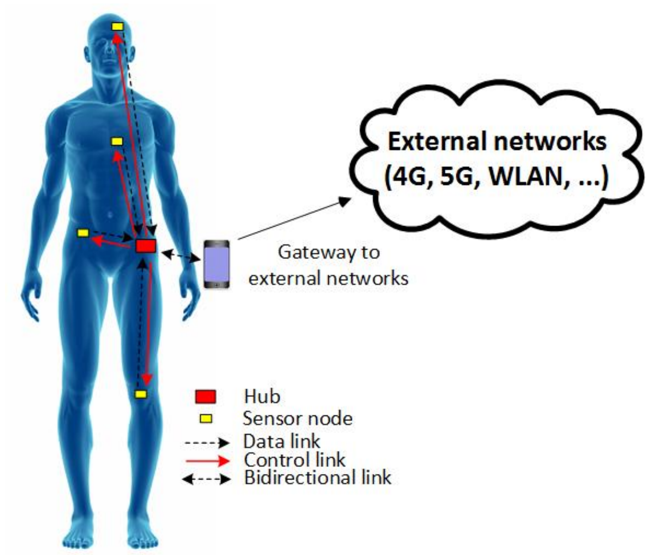

Figure 1. WBAN architecture and connection to external networks.

that are implanted around the body to measure different physiological parameters. In the example application, the implanted medicine diffusion device would include a sensor, medicine dosages, an MCU, a communication unit and a power source. Device must be programmed to take care of the medicine dosing according to a predefined schedule. However, device should be reconfigurable and able to communicate outside the body to report sensor readings and the amount of diffused medicine to the hub node.

Different sensors' observations can be collected to perform a centralized or even distributed medicine diffusion to different parts of the body. In the studied architecture, the data collected to the hub will be sent to a gateway node, e.g., smart phone as illustrated in the Figure 1. The hub can physically reside also in the smart phone if it is equipped with the same radio air interface as the sensor nodes. In this paper, the communication between the hub and sensor nodes is considered since the proposed solution targets to improve energy efficiency of WBAN.

In this work the energy efficiency of communication is enabled by using the IEEE Std. 802.15.6 IR-UWB transmitter-only radio for data transmissions from the sensor nodes to the hub. In addition WUR is deployed in the sensor nodes to receive control messages from the hub node. The proposed dual-radio approach for the medicine diffusion device is illustrated in Figure 2.

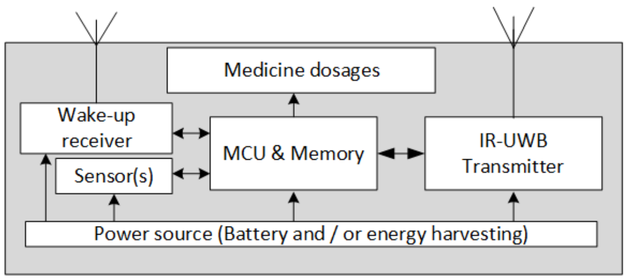

Figure 2. Medicine diffusion device architecture.

By using this approach, there is no need to implement UWB receiver to the sensor node which is more power consuming than UWB transmitter [20]. The hub node includes IEEE Std. 802.15.6 IR-UWB and MICS band radios. UWB receiver is used to receive data from the sensor node and the MICS band transmitter is used to transmit WUS and the control messages to the sensor nodes.

WUR enables that the control channel receiver does not need to listen the channel according to a duty cycle. Control messages can include e.g., queries about the state of the sensor node or reporting frequency adjusting or dosage amount adjusting by using few bits messages. For the MAC, the GWR-MAC protocol's sink-initiated mode can be used [1]. I.e., when the hub will wake-up the sensor node by transmitting the WUS, the sensor node will send acknowledgement (ACK). The hub (sink) node will then send control message back to the sensor node(s). If the hub node queries data from sensor nodes after waking-up them, it will send a beacon message and sensor nodes can then send data to the hub. For other type of sensor nodes, the control channel can be implemented also using some other frequency band by following the proposed dual-radio approach designed for asymmetric traffic.

IV. PERFORMANCE EVALUATION

The proposed communication solution energy efficiency has been evaluated analytically and by using Matlab software. The analytical model has been revised based on author's previous works [1] and [21]. The model enables to explore UWB-WUR WBAN energy consumption in comparison to conventional DCR-based WBAN. Moreover, WUR design tradeoffs (sensitivity, data rate and power consumption) affect to energy consumption has been modeled in this work. The parameters that are used in the performance evaluation are shown in Table 1. Parameters have been selected to account for state-of-the-art techniques.

Table 1. Parameters for performance evaluation.

Parameter	Definition	Value
N_S	Number of sensor nodes	6
N_H	Number of hub nodes	1
$P_{TX,S}$	IR-UWB TX power consumption in sensor node	12 mW
$P_{TX,H}$	IR-UWB TX power consumption in hub node	12 mW
$P_{RX,S}$	IR-UWB RX mode power consumption in sensor node	18 mW
$P_{RX,H}$	IR-UWB RX mode power consumption in hub node	18 mW
$P_{TX,H}$	MICS band TX mode power consumption in hub node [15]	12 mW
$P_{RX,S}$	WUR power consumption [16]	44 µW
R_W	WUR data rate	1-200 kbps
R_S	IR-UWB data rate	0.487 Mbps
F_{CM}	Frequency of control messages	1/y – 1/s
D_P	Duty cycle percentage of conventional reference solution	0.3 – 2.5%
D_F	Frequency of data transmissions	1 / h
L_D	Data packet length	255 oct

A. Energy consumption comparison

Energy consumption model has been developed to evaluate how the UWB-WUR dual-radio approach performs against conventional duty-cycling based single radio approach. In calculations it has been assumed that the sensor nodes will periodically transmit a data packet to the hub once per hour. The number of control (CTRL) messages from the hub to sensor nodes varies between one per year and one per second. In WUR network case, the model takes into account the energy consumption due to frequent data transmissions and receptions and WUS transmissions and receptions depending on the CTRL message frequency. While in DCR case the model takes into account: the energy consumed during channel listening according to duty cycling; handshaking required for CTRL message transmission; and the energy consumption due to frequent data transmissions and receptions.

For UWB-WUR network case the energy consumption is calculated as

$$E_{WUR}^{TOT}(\varepsilon,t,\beta) = N_S(E_{RX,WUS}(\varepsilon,t,\beta) + 2E_{TX,ACK}(\varepsilon,t,\beta) + E_{RX,CTRL}(\varepsilon,t,\beta) + E_C(t) + E_{TX,D}(\varepsilon,t,\beta)) + N_H(E_{TX,WUS}(\varepsilon,t,\beta) + 2E_{RX,ACK}(\varepsilon,t,\beta) + E_{TX,CTRL}(\varepsilon,t,\beta) + E_{RX,ACK}(\varepsilon,t,\beta) + E_{RX,D}(\varepsilon,t,\beta)) \quad (1)$$

and in DCR network case as

$$E_{DCR}^{TOT}(\varepsilon,\lambda,t,\beta) = N_S(E_{RX,DC}(\lambda,t) + E_{RX,RTS}(\varepsilon,t,\beta) + E_{TX,CTS}(\varepsilon,t,\beta) + E_{RX,CTRL}(\varepsilon,t,\beta) + E_{TX,ACK}(\varepsilon,t,\beta) + E_{TX,D}(\varepsilon,t,\beta)) + N_H(E_{TX,RTS}(\varepsilon,t,\beta) + E_{RX,CTS}(\varepsilon,t,\beta) + E_{TX,CTRL}(\varepsilon,t,\beta) + E_{RX,ACK}(\varepsilon,t,\beta) + E_{RX,D}(\varepsilon,t,\beta)) \quad (2)$$

where ε is the amount of CTRL messages during time t, β is the bit error probability, N_S is the amount of sensor nodes, N_H is the amount of hub nodes, $E_{RX,WUS}$ is the energy consumption of wake-up signal reception, $E_{TX,WUS}$ is the energy consumption of wake-up signal transmission, $E_{TX,ACK}$ is the energy consumption of ACK transmission, $E_{RX,ACK}$ is the energy consumption of ACK reception, $E_{RX,CTRL}$ is the energy consumption of CTRL message reception, $E_{TX,CTRL}$ is the energy consumption of CTRL message transmission, E_C is the constant energy consumption of WUR, $E_{RX,DC}$ is the energy consumption of channel listening according to the duty cycle λ, $E_{TX,RTS}$ and $E_{RX,RTS}$ are the energy consumption of RTS message transmission and reception, respectively, $E_{TX,CTS}$ and $E_{RX,RTS}$ are the energy consumption of CTS message transmission and reception, respectively, and $E_{TX,D}$ and $E_{RX,D}$ are the energy consumption of data transmissions and receptions, respectively.

Figure 3 shows the energy consumption comparison for WBANs based on the proposed dual-radio approach and the DCR approach based on duty cycling. Results are given for different duty cycle values between 0.3% and 2.5%. Error-free transmissions has been assumed for both approaches. It can be observed that dual-radio approach consumes less energy than

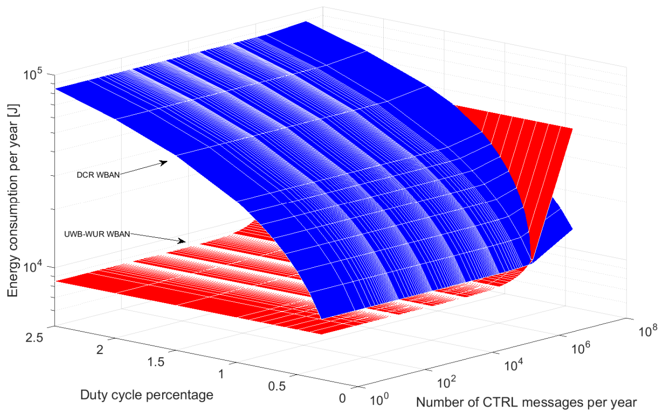

Figure 3. Energy consumption comparison for UWB-WUR and DCR WBANs.

the DCR based WBAN until the number of CTRL messages per year increases to approximately to three per minute. After that point the DCR network with the lowest duty cycle consumes less energy.

B. WUR design tradeoffs

Figure 4 shows energy consumption results for WURs with different parameters. In this case only the WUS transmissions and receptions are taken into account to clearly illustrate the WUR design parameters tradeoff. Three different WUR settings are evaluated: 1) WUR with data rate R = 1 kbps and required transmitter's power consumption P_{Tx} = 12 mW; 2) WUR with R = 50 kbps and P_{Tx} = 24 mW; 3) WUR with data rate R = 200 kbps and P_{Tx} = 45 mW. The rationale behind these parameters is that low data rate WUR can be designed to be more sensitive. I.e., lower transmit power is required to achieve successful wake-up signal detection. E.g., in [22] it is shown that transmitter's power consumption is halved when output power is reduced by 25 dBm. Sensitivities for proposed WUR solutions varies, i.e., the setting 1) corresponds to most sensitive receiver and 3) the least sensitive. The results of Figure 4 are calculated for a single link taking into account TX and RX energy consumption with parameters that are given above. From the results it can be observed that when the number of wake-ups is more than ten per hour, the energy consumption of WUR with lowest data rate performance starts to increase. The reason is that, since the data rate is low, the WUS transmission and reception take more time and their contribution to energy consumption starts to be remarkable, even the required transmission power is lowest in that case.

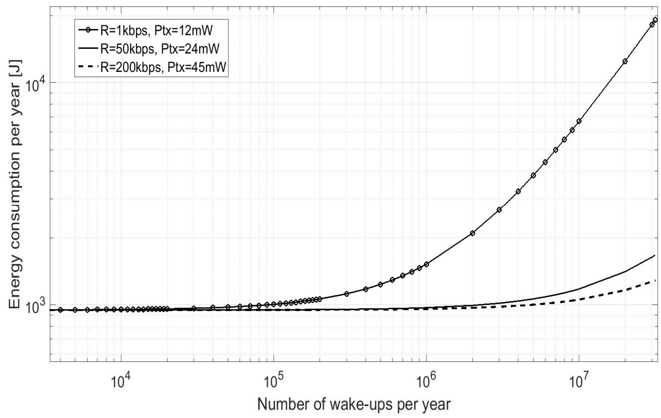

Figure 4. Energy consumption comparison for WURs with different data rate, sensitivity and required transmission power values.

C. Energy efficiency

Energy efficiency model from previous work [1] has been revised and used here to compare UWB-WUR network with different WUR parameters and DCR-based network in the same scenario as in Section IV A. At first the energy consumption with respect to the amount of CTRL messages is derived as [1]

$$E_{\varepsilon}(\varepsilon,\lambda,t,\beta)=\frac{E(\varepsilon,\lambda,t,\beta)}{\varepsilon} \tag{3}$$

where nominator is calculated for WUR approach by using Eq. (1) and for DCR approach by using Eq. (2). Then the energy efficiency can be calculated as [1]

$$\eta(\varepsilon,\lambda,t,\beta)=\frac{\min(E(\varepsilon,\Delta,t,\beta))}{E(\varepsilon,\lambda,t,\beta)} \tag{4}$$

where the duty cycle value set $\Delta=(0,1]$. In the UWB-WUR approach case the duty cycle is one since it is continuously able to receiver wake-up signal. By using Eq. (4) the energy efficiency can be clearly compared by taking into account the amount of CTRL messages which is an important parameter since it defines the frequency of required wake-ups in the studied scenario.

Figure 5 shows energy efficiency results for the WUR settings introduced in Section IV B in comparison to DCR-based WBAN. It can be observed that the WUR1 is more energy efficient than the lowest duty cycle approach (0.3%) until the number of CTRL messages per year increases to approximately to three per minute as was observed also from results of Figure 3. Moreover it can be observed that the other WUR setting introduced above will remain more energy efficient than DCR WBAN for the whole range of number of CTRL message transmissions.

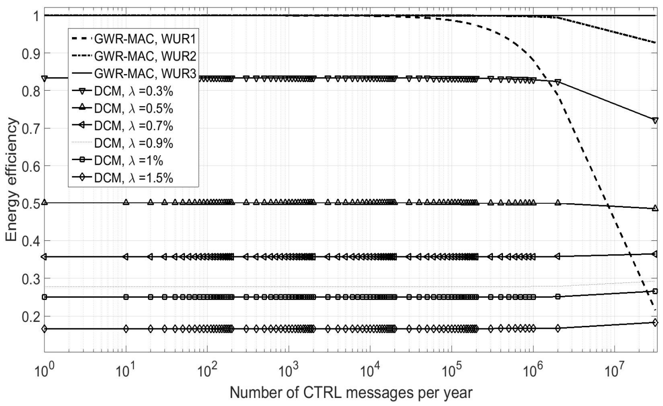

Figure 5. Energy efficiency comparison for UWB-WUR and DCR WBANs.

V. Conclusion

A dual-radio approach for asymmetric communication links in WBANs was introduced in this paper. Approach is based on wake-up receiver usage so that sensor nodes will include IR-UWB in transmit-only mode for data transmissions (uplink), and WUR is used for control message receptions from the hub node (downlink). The proposed approach is enabling that idle listening will not occur at the sensor nodes which presumably can improve energy efficiency especially when the downlink traffic does not occur often. Analytical energy consumption comparison results show that the proposed approach is more energy efficient than the conventional duty cycle approach in the studied scenarios. Moreover, results for WURs with different parameters were shown to illustrate how it effects to the energy efficiency. Results show clearly that proposed approach has large potential to improve the energy efficiency in WBANs which have asymmetric traffic for uplink and downlink. Furthermore, solution can be useful also in other scenarios such as vehicle- or robot-BANs where similar dual-radio communication principle can be applied.

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