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WBAN Energy Efficiency and Dependability Improvement Utilizing Wake-Up Receiver

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SUMMARY This paper discusses the perspectives of using a wake-up receiver (WUR) in wireless body area network (WBAN) applications with event-driven data transfers. First we compare energy efficiency between the WUR-based and the duty-cycled medium access control protocol - based IEEE 802.15.6 compliant WBAN. Then, we review the architectures of state-of-the-art WURs and discuss their suitability for WBANs. The presented results clearly show that the radio frequency envelope detection based architecture features the lowest power consumption at a cost of sensitivity. The other architectures are capable of providing better sensitivity, but consume more power. Finally, we propose the design modification that enables using a WUR to receive the control commands beside the wake-up signals. The presented results reveal that use of this feature does not require complex modifications of the current architectures, but enables to improve energy efficiency and latency for small data blocks transfers.
key words: *event-driven application, dependability, low-latency, low-power, receiver architecture, wireless body area network*

1. Introduction

With the growth of the average age of population in the developed countries the importance of the health care applications based on the wireless body area network (WBAN) technology has increased drastically [1]. In medicine-related applications, the dependability is the core requirement. But even if a device is capable of robustly monitoring the human body functions and communicating the results reliably, this does not worth much if the lifetime of the device is very poor. To enable dependable network, a WBAN node should have a long lifetime. In this work we focus on the problem of increasing the WBAN lifetime by using the wake-up receivers (WUR).

Dependability for WBAN has been discussed in IEEE 802.15 Interest Group on Dependability where one of the focus areas is physical layer dependability in medical applications. Network dependability covers many areas, such as reliability, security, robustness and fault tolerance even in unpredictable environments [2].

A typical WUR is a sufficiently simple radio receiver with very low-power consumption, which is integrated into a sensor network node (see Fig. 1). The WUR constantly listens to the radio channel and immediately awakes the main microcontroller (MCU) of the node once the proper wake-up signal is detected. Then, an MCU might use the full-featured radio frequency (RF) transceiver for the actual communication. The two major advantages of using WURs are: significant energy savings and short response times. The former is achieved by keeping the most energy hungry components of a node, namely the MCU and RF transceiver, in sleep mode. The latter becomes possible since the WUR is active all the time. The price for this is the increase in the complexity, size and cost of the node.

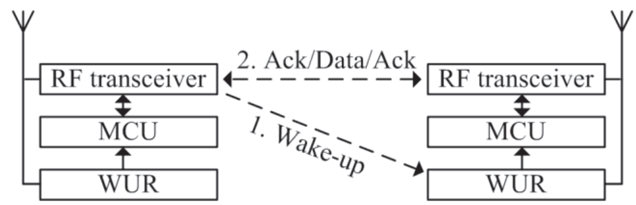

Fig. 1 Example of communication between WUR equipped sensor nodes. The RF transceiver operates in the same frequency band and is capable of issuing the low-data rate wake-up signal for WUR.

The progress in WUR hardware designs in the last decade enables us to expect that in the very near future WURs might become an integral part of the various commercial applications. The power consumption of the current state-of-the-art (SotA) designs is already very promising and is well below 100 μW, i.e., 100 times less than the consumption of a typical commercial RF transceiver. Some of the proposed research prototypes, e.g., [3], [4], even have the consumption of less than 10 μW and are capable of providing years of constant channel listening being powered by a single coin-size battery. Meanwhile, due to their low-power nature, the sensitivity of WURs is often much lower than the one of the RF transceivers. This requires a transmitter to use more power for reaching WURs, than the power needed for reaching the RF transceivers at the same distance.

This paper has three major contributions. First, in Sect. 2 we compare the network performance of the WUR-enabled and the duty-cycle medium access control (MAC) based and show under which conditions each of the approaches should be used. Second, we review the SotA WUR architectures and discuss their suitability for WBAN scenario in Sect. 3. Finally, in Sect. 4 we propose an extension that enables WUR to be used as a means of data transfer and point out few scenarios where this feature is useful.

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2. Duty-Cycle MAC vs. WUR Based WBANs

Often used approach for saving the energy in WBANs is the duty-cycle based MAC (DCM) protocols. In a DCM protocol, a receiver periodically switches between two states: active channel listening and sleep. To decrease the energy consumption, the duty-cycle might be reduced; however this causes increase of the communication delays.

A generic WUR based MAC (GWR-MAC) protocol, which is scalable to a variety of WBAN scenarios has been proposed in [5]. The GWR-MAC protocol defines a bidirectional wake-up procedure followed by data transmission. The wake-up procedure of GWR-MAC is designed keeping in mind both the source-initiated and sink-initiated cases. In [5], [6], authors have proposed an analytical model, which can be used to compare energy efficiency of the GWR-MAC based and conventional DCM based networks as a function of number of events in a two-tier WBAN. In that model energy efficiency for the IEEE 802.15.6 standard [7] based WBAN is defined as

$$\eta(\varepsilon, \lambda, t, \beta) = \frac{\min(E(\varepsilon, \Lambda, t, \beta))}{E(\varepsilon, \lambda, t, \beta)}, \tag{1}$$

where E is the network energy consumption over time period t, ε is the number of events during t, λ is duty-cycle and β is bit error probability. Each event includes transmission of a data packet from a sensor to the hub about the sensed event. In (1), the minimum of E can be calculated over the duty-cycle value set $\Lambda = (0,1]$. Note that $\Lambda = 1$ corresponds also to the WUR case since the receiver is listening the channel continuously. The metric introduced in (1) defines the maximum energy efficiency to be one and enables comparison of the WUR and DCM based networks.

To study the effect of WUR sensitivity vs. power consumption trade-off, we calculated results using three different WUR parameters, which are shown in Table 1. Typical SotA performance values are used in WUR1 and WUR2 for power consumption and sensitivity. WUR3 sensitivity is set equal to transceiver used by DCM. In calculations is assumed that data packet payload is 255 bytes and communication is error free ($\beta = 0$). The other assumptions of the model and its detailed description can be found from [5].

The chart illustrating energy efficiency for GWR-MAC and DCM based networks as a function of number of events per hour is presented in Fig. 2. It can be observed that the GWR-MAC based network outperforms the DCM based network's lowest duty cycle case ($\lambda = 0.5\%$) until the number of events increases to approximately 13 per hour. When compared to DCM network with $\lambda = 3\%$, the WUR based approach is more energy efficient if the number of events is below 75 per hour.

The comparison of the results for different WURs shows that WUR's receive (Rx) mode power consumption has remarkable effect to the total energy efficiency. The GWR-MAC network based on WUR1, which features worst sensitivity and has the lowest consumption, has the highest energy efficiency even though it requires highest power used by the transmitter. WUR3 has highest Rx mode power consumption, which leads to lower energy efficiency when events occur rarely. This observation highlights the importance of constant mode power consumption minimization for WURs. When the number of events increases above ten per hour, the energy consumption of data communication starts to dominate in the network overall energy consumption and the difference between WUR's energy efficiency is not visible anymore. As one can see, the results of Fig. 2 show that the WUR based approach is significantly more energy efficient than duty-cycle based approach when the event frequency is low.

Table 1 Parameters used for different radios in energy efficiency comparison.

Radio	Sensitivity	Tx power	Data rate	Power consumption	
				Tx mode [8]	Rx mode
WUR1	-70 dBm	0 dBm	200 kbps	52.2 mW	5 μW
WUR2	-80 dBm	-10 dBm	200 kbps	33.9 mW	10 μW
WUR3	-95 dBm	-25 dBm	200 kbps	25.5 mW	50 μW
DCM	-95 dBm	-25 dBm	971 kbps	25.5 mW	56 mW [8]

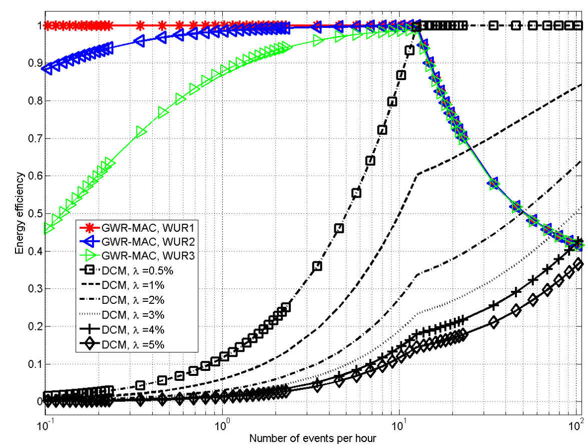

Fig. 2 Energy efficiency comparison for WUR based and DCM based network a function of number of events per hour.

3. WUR Architectures

Recently published WUR design solutions use a variety of different receiver architectures, whereas data receivers typically use direct conversion or low-intermediate frequency (low-IF) architectures. In this paper we divided WUR architectures based on how the front-end operates before signal processing at baseband. Proposed WUR solutions are divided here into following groups:

- RF envelope detection (RFED),
- matched filter (MF),
- superheterodyne (SHR),
- direct-conversion (DiCo) and low-IF,
- uncertain intermediate frequency (U-IF),
- injection-locking (IL) and
- superregenerative oscillator (SRO).

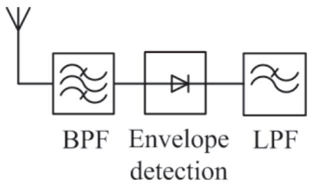

Fig. 3 Typical front-end of an RFED architecture.

The following sections will introduce and compare these architectures, paying special attention to the active power consumption and sensitivity. Integrated circuit (IC) implementation is also important especially for WBAN applications, because the sensor nodes should be as small and light as possible. There are WURs that utilize duty-cycling, but it is seen as protocol level energy saving method. Therefore, only active power consumption is taken into account.

3.1 RF Envelope Detector

In RFED based receiver's RF is directly converted to baseband as a part of envelope detection, thus omitting the need for local oscillator (LO) for down conversion. Figure 3 shows a typical RFED architecture. Envelope detection detects a signal from wide bandwidth. To ensure low-noise at the envelope detector input, the bandwidth of the band pass filter (BPF) should be fitted to wake-up signal's bandwidth.

In [3] RFED-based WUR employs external surface acoustic wave (SAW) filter with matching network to lower out-of-band interference. To improve signal-to-noise ratio (SNR) after RF envelope detection, low-power analog correlation unit is utilized to provide coding gain for 64-bit wake-up signals. Correlation is done after low-pass filtering and amplification at the baseband. Achieved sensitivity is −71 dBm and the power consumption is 2.4 μW.

The presented WUR in [9] reduces the receiver's noise by utilizing double sampling technique. After envelope detection the signal is down converted to 10 MHz instead of DC in order to keep the signal away from the $1/f$ noise region. Then the signal is amplified and sampled to baseband and at the same time the $1/f$ noise is up converted and filtered out. This enables to decrease the spectral density of the noise. The reported power consumption of the receiver is 51 μW and the sensitivity is −75 dBm.

At the baseband of RFED WUR proposed in [10], the analog signal is converted into digital by a continuous-time $\Sigma\Delta$ converter, which oversamples the received signals to improve SNR and also reduces probability of false wake-ups. The digital signal passes through a decimation filter, which triggers the wake-up. The WUR can operate at two frequencies: 2.4 GHz or 5.8 GHz. The band is selected by adjusting impedance matching. The sensitivities of WUR are −65 dBm and −50 dBm for 2.4 and 5.8 GHz respectively. The receiver consumes 10 μW of power.

Being the most straightforward option for power detection, the number of RFED WURs exceeds the number of WURs featuring the other architectures. More RFED-based WURs have been reported, e.g., in [4], [11]–[17].

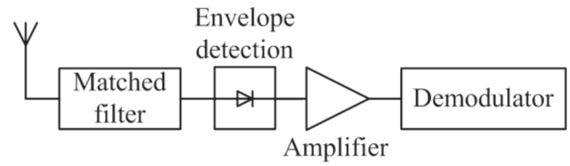

Fig. 4 Matched filter based WUR architecture.

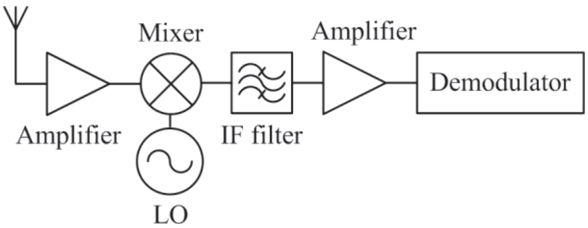

Fig. 5 Analog superheterodyne architecture with one IF-stage.

3.2 Matched Filter

In-band interference is a major challenge for receiver architectures that are based on received signal power. With a spread spectrum technique, the signal is spread in frequency domain, which makes it more resistant against interference.

In [18], a passive SAW MF is designed to match an 11-chip Barker spreading coded wake-up signal. The architecture is shown in Fig. 4. After the SAW MF the signal is first detected and amplified and then demodulated. The proposed receiver was implemented using discrete components. The sensitivity is −60 dBm and power consumption is 99 μW.

3.3 Superheterodyne

Although getting less attention in integrated transceivers, one possible option for a WUR is an analog SHR shown in Fig. 5. Good sensitivity performance is achieved at the cost of power consumption, which significantly exceeds the one of other architectures. To handle this issue, the duty-cycling is often employed [19], [20]. But their active power consumptions are over mW, significantly more than WURs based on the other architectures.

3.4 Sub-Sampling

A differential sample and hold (S&H) circuit with sampling frequency of 136 MHz and 27.5 dB noise figure (NF) combined with IF-amplifier is proposed in [21]. First, the radio signal is down converted from RF (915 MHz) to IF (37 MHz). Then, the S&H output is fed to a multistage amplifier, after which the envelope is detected and the signal is converted to digital. On-chip digital circuitry detects whether the wake-up code is valid. The receiver operates at data rates of either 10 kbps or 200 kbps and consumes 16 μW or 22 μW, respectively. Even though S&H circuit has

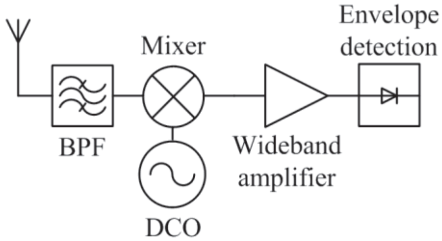

Fig. 6 Uncertain-IF receiver architecture.

a high NF, the authors reported achieving the sensitivities of −78 dBm and −75 dBm for 10 kbps and 200 kbps rate, respectively.

3.5 Uncertain Intermediate Frequency

Accurate RF synthesizer designs are expensive in terms of power consumption. Therefore, the U-IF receiver architecture makes use of RF synthesizers that have very low-power consumption obtained at the cost of poor frequency stability. Hence after down conversion the IF can be located in a wide frequency range.

Bulk acoustic wave (BAW) resonator is used as a filter at the front-end to make U-IF based WUR introduced in [22] more robust against interference. It uses free-running ring oscillator and it is calibrated to oscillate between 1.9 and 2.1 GHz. The mixer down converts 2 GHz on-off keying (OOK) modulated RF signals into IF, which lies between 1 MHz and 101 MHz. The wideband IF amplification is used to amplify incoming signal before envelope detection that converts the signal from IF to baseband. Sensitivity of −72 dBm is achieved with power consumption of 52 μW.

The WUR introduced in [23] combines U-IF and sub-sampling structures. Sub-sampling is used to down convert the RF signal omitting the need for a mixer and a LO operating at high frequency. With sub-sampling, LO frequency (200 MHz) can be significantly lower than the 915 MHz RF frequency. Since ring oscillator is employed to generate LO frequency, the center frequency varies depending, e.g., on temperature, which creates the uncertain-IF. Wideband IF amplifier is employed before the signal is down converted to baseband by envelope detection. The sensitivity of WUR is −72 dBm and the power consumption is 28 μW.

3.6 Direct-Conversion and Low Intermediate Frequency

Due to the challenges of flicker noise and DC offset, the DiCo architecture is rarely used in WURs. Instead, low-IF architecture is used, e.g., in [24] the signal is down converted from 925 MHz to 1 MHz IF by a passive mixer and a ring oscillator based phase locked loop (PLL) that generates the LO frequency. At low-IF the signal is amplified and rectified. The receiver consumes 44.2 μW and its sensitivity is −87 dBm. According to [24], the described low-IF receiver is designed to receive only the first part of the wake-up signal. If the signal has correct length, the second part is received with a more power consuming low-IF design. It consist of LNA operating at RF, mixer with low-noise free-running LO, BPF, a limiter, a buffer followed by FPGA, which handles the demodulation. The power consumption of this receiver is 1.3 mW.

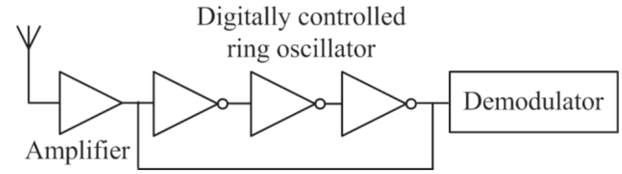

Fig. 7 Receiver architecture based on ring oscillator that locks injection signal.

3.7 Injection-Locking

Injection-locking architecture is typically used for frequency shift keying (FSK) modulated signals. If the received carrier frequency is close to oscillator's natural oscillation frequency, coupling will occur. This effect is called as injection locking. If the received carrier frequency is not close enough, injection pulling occurs, i.e., the carrier interferes and it is seen at the oscillator output. In Fig. 7 is shown the digitally controlled oscillator (DCO) that is locked to injected signal.

In [25] it is introduced an IL based FSK WUR which is fabricated to a 1 mm^2 single chip without any external components. The receiver operates in the 80 MHz body channel communication (BCC) band. The WUR is injection locked when the received frequency is close to 80 MHz and injection pulled when 72 MHz signal is received. The oscillator output is fed to an envelope detector. At baseband, the signal is amplified and demodulated. The achieved sensitivity is −62 dBm and the power consumption is 45 μW.

An IL ring oscillator in [26] is designed for the 45 MHz BCC band. The ring oscillator locks the FSK modulated input signal, which is then demodulated directly by a PLL based demodulator. Auto frequency calibration method is used to handle frequency drift in the ring oscillator caused by temperature variations and leakage current. The sensitivity is −62.7 dBm and power consumption is 37.5 μW.

A nine-stage IL ring oscillator is used in [27] to down convert a Medical Implant Communication Service (MICS) band signal to 1.5 MHz IF. The frequency multiplication by nine enables directly locking to the reference frequency without PLL or DLL. Low-IF is utilized since this reduces the effect of $1/f$ noise. The FSK demodulator is digital, and is composed of a comparator and two counters. The IF output is fed to the first counter, the length of each period length is measured by the second counter. While consuming 38 μW of power, the WUR features sensitivity of −75 dBm.

3.8 Superregenerative Oscillator

Superregenerative WUR has in its core the SRO which is periodically switched between stable and unstable states by a quench signal having considerably lower frequency than

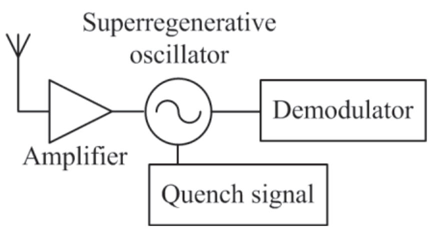

Fig. 8 Quench signal switches SRO between stable and unstable state.

the carrier of the RF signal. The structure of an SRO-based WUR is shown in Fig. 8. The start-up time of oscillations depend on the power of the received radio signal. The difference of SRO oscillation start-up times can be effectively used to detect, e.g., OOK modulated signal.

In the WUR design proposed in [28], the RF signal is sampled directly by a detector oscillator. In order to reduce the power consumption and boost the selectivity, a BAW resonator is used to generate the reference frequency for detector. To prevent feed through from SRO to radio channel, the WUR is equipped with an isolation amplifier. The amplifier and detector oscillator share bias current which enables to reduce the current consumption since those two blocks consume most of the receiver's power. The envelope is detected with a non-linear filter. The sensitivity of −100.5 dBm is achieved at the cost of 400 μW power consumption.

The superregenerative receiver proposed in [29] uses FSK modulation instead of more conventional OOK. Each incoming bit is sampled at two different frequencies, first in f_1 and then the SRO is tuned to f_2 and sampled. Then the signals are rectified and compared, which reveals the received bit. The SRO frequencies f_1 and f_2 are calibrated using SAR algorithm during power up. The reported sensitivity for WUR is −86 dBm and the power consumption is 215 μW.

3.9 Comparison of WURs and Their Architectures

The design of a WUR involves many tradeoffs regarding its selectivity, data rate, power consumption and sensitivity. The power consumption and sensitivity are usually considered to be the most important. As for the data rate – the length of the wake-up packet is usually in the order of few bytes and thus the wake-up signal might be transmitted sufficiently fast even with low data rates. Another aspect, which is especially important for WBAN applications, is the capability of node size minimization. Therefore, we included the CMOS technology to Table 2, which summarizes all the works introduced above.

As one can see, OOK and FSK are the most popular choices for modulation, since those can be effectively demodulated with low-power consuming circuits. The majority of the receivers are scattered to most common industrial, scientific and medical (ISM) frequency bands, although some solutions are developed specifically for MICS band.

Figure 9 shows a comparison of power consumption

Table 2 Wake-up receiver comparison.

Reference	Architecture	Frequency band [MHz]	Modulation	Sensitivity [dBm]	Power consumption [µW]	Data rate [kbps]	CMOS technology [nm]
[3]	RFED	868	OOK	-71	2.4	200	130
[4]	RFED	915	OOK	-41	0.10	100	130
[9]	RFED	915	OOK	-75	51	100	90
[10]	RFED	2400	OOK	-65	10	100	180
[11]	RFED	2400	OOK	-53	7.5	100	120
[12]	RFED	5800	OOK	-44	36	256	130
[13]	RFED	433	GOOK	-51	0.27	5.5	PCB
[14]	RFED	60000	OOK	-68	9	350	180
[15]	RFED	1900	OOK	-56	65	100	90
[16]	RFED	405	OOK	-45.5	0.12	12.5	130
[17]	RFED	2450	OOK	-47	2.3	200	130
[18]	MF	2484	DSSS	-60	99	N/A	PCB
[21]	Sub-s.	915	OOK	-78/-75	16/22	10/200	130
[22]	U-IF	2000	OOK	-72	52	100	90
[23]	U-IF	915	OOK	-70	28	N/A	90
[24]	Low-IF	925	FSK	-87	44/1300	N/A	65
[25]	IL	80	FSK	-62	45	312	180
[26]	IL	45	FSK	-62.7	37.5	200	130
[27]	IL	405	FSK	-75	38	20	130
[28]	SRO	1900	OOK	-100.5	400	5	N/A
[29]	SRO	2400	FSK	-86	215	250	180

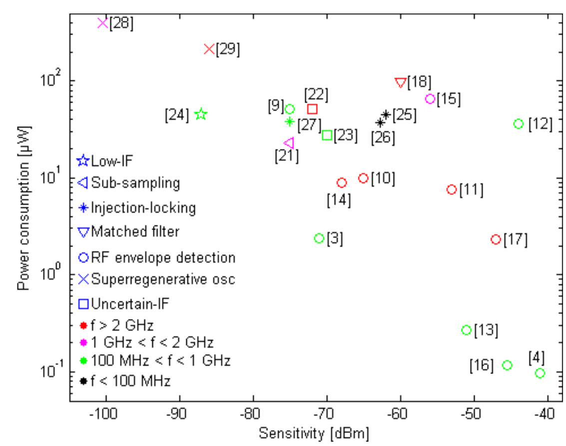

Fig. 9 Comparison between WURs and architectures. See electronic version for frequency bands mapped with colors.

and sensitivity for various WUR architectures. One can observe that RFED based WURs feature low-power consumption at the cost of sensitivity. Therefore, this solution might be used for WBAN applications where the nodes are located close to each other. In the case of long-range links, the other architectures based, e.g., on the superregenerative oscillator or on low-IF, might be more convenient.

4. Possibility of Data Transfer with WUR

As we have shown in Sect. 2, the SotA WURs have potential to improve energy efficiency of WBAN. But the WUR is capable of much more than this. One of the potentially perspective scenarios is to use the WURs also for transferring small blocks of data (e.g., control commands) instead of the data transceiver (see Fig. 1). The major benefit of

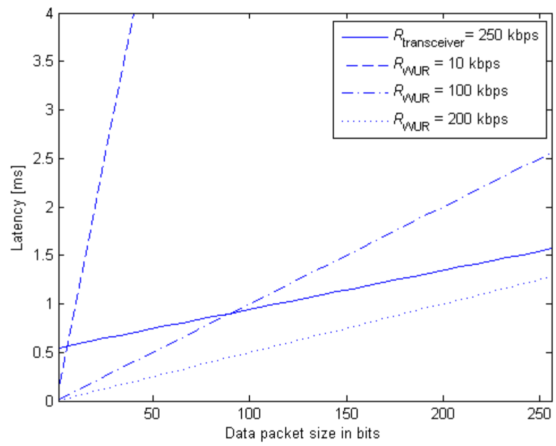

Fig. 10 Small packets are faster to transfer via WUR than via data transceiver.

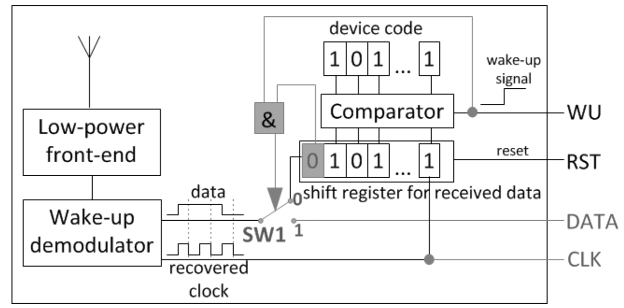

Fig. 11 Architecture of a WUR with data transfer capability. In grey are shown the additional components required to enable receiving the data packets.

this approach is energy efficiency since the consumption of WUR is typically much lower than the one of the data transceiver. Also, given that the amount of data is small, transferring those through WUR might require less time and allows reducing the data channel load. To give an example, blood pressure or electrocardiography measurements having the traffic of 10 bps and 3 kbps respectively [30] might utilize WUR for data transfer. The major drawbacks for using WUR for data transfer are worse sensitivity of a WUR and its vulnerability to interferences.

To give a practical example, we have estimated the time required for transferring the data with an IEEE 802.15.4 [31] compliant CC2520 transceiver [32] and a data-transfer-enabled WUR. Given that the data transferred through WUR follow the wake-up code, the time for data transferring via WUR can be estimated as

$$t_{WUR} = \frac{N_{data}}{R_{WUR}}, \tag{2}$$

where N_{data} is the packet size in bits and R_{WUR} is the WUR data rate. For the data transceiver the time for transferring the data is

$$t_{transceiver} = t_{startup} + \frac{N_{data} + N_{overhead}}{R_{transceiver}}, \tag{3}$$

where $t_{startup}$ is the data transceiver startup time, which is 492 μs [32] and includes the time required for starting up the voltage regulator and oscillators, writing the registers specifying the required operation mode and enabling the receive circuitry. $N_{overhead}$ is 17 byte packet overhead [31].

Figure 10 shows latency as a function of packet size for different data rates for WURs and for IEEE 802.15.4 compatible transceiver. The presented results reveal that a WUR with R_{WUR} = 10 kbps will outperform the data transceiver only if the length of the data is below 5 bits. With the increase of WUR's data rate to 100 and 200 kbps, up to 88 and 550 bits, respectively, can be delivered faster via WUR than via data radio. So, as one can see, short blocks of data can be transferred via WUR faster than with a data transceiver. The major reason for this is that although having higher throughput, the data transceiver needs some time for waking-up and has some extra overheads. However, these results do not take into account bit errors. Data transceivers are much more reliable since they can detect and correct bit errors.

From the power consumption perspective, while receiving a data packet the WUR consumes considerably less energy than data transceiver. But, as shown in Sect. 2, the transmitter might need to use higher transmit power resulting in higher energy consumption, since WURs are less sensitive than data transceivers.

The implementation of the proposed concept in practice does not cause significant increase neither for the WUR's complexity nor for its energy consumption. A possible architecture of the WUR supporting data transfer is depicted in Fig. 11. In grey are shown the components added to a WUR to enable the data transfer. To start the data transferring, the proper wake-up code which triggers the wake-up signal should be followed by a logical "1" bit, which causes commutation of switch SW1 to position 1. Then, the data from the demodulator are output to DATA line for further processing by the MCU of a sensor node (see Fig. 1). Given that the wake-up demodulator besides the data provides also the recovered clock signal, for receiving the data the MCU might use the basic serial peripheral interface (SPI) module operating in slave mode. Once the data transfer is finished, the main controller can use RST line to switch WUR back to code awaiting mode.

The proposed data transfer mechanism using WURs can be valuable for different real-life WBAN scenarios. First of all, it can be used for including the specific commands or data for sensor nodes to be executed after wake-up (e.g., make a specific measurement or switch the data radio to a specific frequency). The other possibility is to use WUR-based data channel as a back-up option when the data channel is blocked in order to increase the reliability of the whole system.

5. Conclusions

In this paper we have shown that WUR-equipped WBAN network enables energy savings in applications where communication is event-driven (e.g., alarms issued on threshold exceeding). We have compared the existing WURs and their architectures. The presented results show that the RF envelope detection architecture is suitable for WBAN applications where nodes are close to each other and other architectures should be used if the long transmission range is required. Finally, we proposed a design which enables to implement a WUR capable for receiving small control commands beside wake-up signal.

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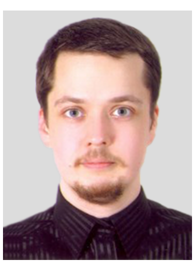

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