Nano-Power Wireless Wake-Up Receiver With Serial Peripheral Interface

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***Abstract*—We designed, implemented, tested and measured an ultra low power Wake Up Receiver (WUR), intended for use in Wireless Body Area Networks (WBAN). Gaussian On-Off Keying (GOOK) and Pulse Width Modulation (PWM) are used to modulate and encode, respectively, the preamble signal. The receiver incorporates a decoder to enable Serial Peripheral Interface (SPI). WUR was also comprehensively tested for power consumption and robustness to RF interference from wireless devices commonly found in the vicinity of persons utilising WBAN technology. Our results and comparative evaluation demonstrate that the achieved listening power of $270\mathrm{nW}$ for the Wake Up Receiver is significantly lower power consumption than for the other state-of-the-art. The proposed preamble detection scheme can significantly reduce false wake ups due to other wireless devices in a WBAN. Additionally, SPI significantly reduces the overall power consumption for packet reception and decoding.**

***Index Terms*—Ultra Low Power, Wake Up Receiver, WBAN, WSN.**

I. INTRODUCTION

WIRELESS Body Area Networks have been a very popular area of research in recent years. The main research effort in this area focuses on reducing the communication power consumption of the WBAN sensors, as the radio transceiver is one of the highest power consumers in WBAN. Accordingly, several techniques have been proposed to minimise the transceiver's duty cycle (the percentage of time during which it is in an active state). Whilst reducing the duty cycle helps to save power, it severely limits network flexibility. The transceiver's power consumption while listening idly on a channel can approach, or exceed, power consumption during data transmission. Therefore, if there is a need for asynchronous events to be initiated by the network co-ordinator, considerable energy must be spent by individual devices on idle listening. To avoid wasting energy in this way, WBANs can benefit significantly from utilising an ultra-low-power wireless receiver which assumes responsibility for listening to identify asynchronous signals, thereby allowing the primary transceiver to be shut down.

There are two types of low power listening devices. A wake-up circuit simply wakes up every device in the proximity of the wake-up signal sender, while a more sophisticated Wake Up Receiver can receive a simple command which identifies and subsequently wakes up only the sensor being addressed. We need therefore to distinguish "wake up signal" and "wake up packet". Wake up signal is the signal sent to the nearby wake-up module and can be used for waking up the sensor by the wake-up interrupt (WUp-Int). Wake up packet is the packet of information that triggers WUp-Int but can contain address and command information. A good wake-up system should switch the main receiver on only if the wake up was intended for this sensor. It also should not consume much power for decoding the address and reading the command.

Energy consumption requirements for WBAN are critical. The WUR will be active for extended periods of time while the other components are either in sleep mode or shut down entirely. Therefore, its power consumption while listening idly should be in the same range as the power consumption of the other devices while in sleep mode (i.e. less than $1\mu\mathrm{W}$).

The WUR module should also reject false wake up signals as much as possible. These can cause the sensor to be woken up unnecessarily, wasting battery energy. In a normal WBAN, false wake-up signals from outside sources can be quite frequent. There are usually a number of high power transmitting devices in the vicinity and a low-power architecture is required which will reject those false signals without waking up the sensor.

The rest of the paper is organised as follows: Section 2 outlines related work in the area of the wake up receivers. Section 3 presents a typical application of a wake up receiver, and the requirements for a WUR in a WBAN. Section 4 details the idea behind the wake up receiver and explains the receiver's circuit architecture. Section 5 presents the receiver communication and electrical characteristics. Sections 6 presents comparisons with the state of the art receivers, while Section 7 makes some concluding remarks.

II. RELATED WORK

The basic need for a WUR is to have a dedicated circuit that can continuously listen to a wireless channel and trigger events without any latency, consuming less power than the regular transceiver. This increases network flexibility and reduces overall power consumption. Advantages of wake up radio were presented in [1] where it was estimated that a specialised radio interface could consume as little energy as $1\mu\mathrm{W}$.

In order to classify the related work, we will distinguish two groups of RF wake up systems.

The first group are the wake up circuits. They can have very low power consumption, but these only detect the activity on a channel, and cannot distinguish a wake up signal from other RF activity of sufficient power. They are mostly realised using a charge pump. This was first presented and simulated in [2]. This circuit consumes no power, and it realised using Schottky diodes. A similar solution using MOSFET is presented in

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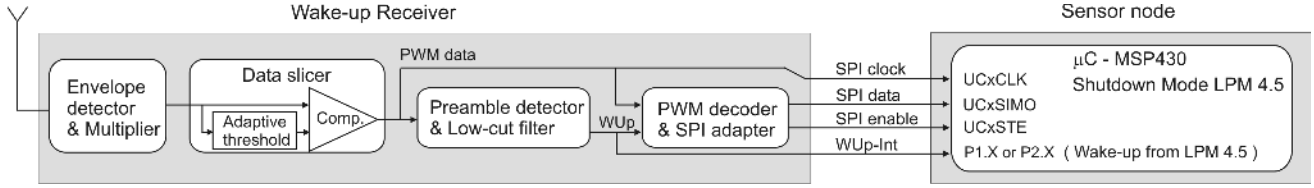

Fig. 1. Wake Up Receiver Overview

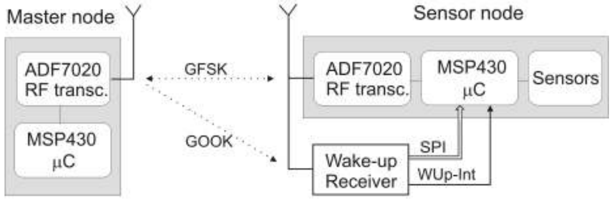

Fig. 2. Wake Up Receiver Application

[3]. Also, battery assisted (semi passive) RFID tags demand similar solutions for their “power-on” sensing circuitry as explained in [4]. An RF field detector was presented as a low power wake up method that could be used in semi passive RFID tags [5]. Another design, with a “power-on” circuit based on a multi stage charge pump is presented in [6]. A complete micro-power sensor node with RF quasi-passive wake-up circuit is presented in [7].

The second group of RF wake up systems is referred to as Wake-up Receivers. Besides the capability to generate a wake-up signal, they have the ability to demodulate and decode some packet of information following the signal, that can be used for addressing. An addressing mechanism is needed to reduce the power consumption used during network formation, and if the wake up receiver can receive some command, the Media Access Control (MAC) data communication protocol can be simplified for low power consumption.

A low power WUR that has these addressing capabilities is presented in [8]. A solution with a Schottky voltage doubler followed by a programmable amplifier and integrator is developed in [9]. Another approach based on a zero-bias Schottky voltage doubler (charge pump, envelope detector), is simulated in [10]. A design based solely on amplifiers is presented in [11]. A bloom filter solution is presented in [12]. Finally, [13] proposes a WUR that has a dedicated low power microcontroller for packet decoding. Our radio design belongs to the Wake Up Receiver group.

III. WAKE UP RECEIVER APPLICATION AND REQUIREMENTS

A typical implementation of a dedicated WUR in a wireless sensor device is as an additional circuit to an existing wireless transceiver. The WUR should communicate with the device’s microcontroller via some standard interface, and ideally re-use the transceiver’s antenna and communication frequency. A typical application is in a WBAN network with ranges less than $2\mathrm{m}$. For this scenario, there is a dedicated Master Node that acts as a network coordinator. This device sends wake up signals, and receive data packets from the sensors.

Our example of a typical WBAN application can be seen in Fig.2. It shows a sensor node based on the Texas Instruments MSP430 microcontroller and the Analog Devices AFD7020 wireless transceiver. The transceiver’s Gaussian Frequency Shift Keying (GFSK) mode is used for data transmission and Gaussian On-Off Keying (GOOK) Pulse Width Modulated (PWM) mode is used for wake up packets. The WUR detects the preamble (wake up signal), generates the interrupt (WUp-Int) which then wakes up the MSP430 from power down mode (LPM4.5) to Low Power Mode 3 (LPM3), to read the demodulated wake up packet as a digital stream on the SPI. For this WUR to be practical, it must fulfill the following requirements:

1) *Very low power consumption*
    a) Very low WUR power consumption
    The WUR remains active for extended periods of time (depending on the MAC protocol) while the rest of the node is in sleep mode.
    b) Small contribution to overall power consumption
    The WUR’s effect on the overall power consumption of the sensor node should be minimal
2) *Minimise the false wake up signals*
    a) Low ratio of false-to-true wake up signal detection
    Every wake-up must switch on at least a microprocessor to analyse the reason for waking, or in the worse case switch on a power-hungry receiver expecting a longer command. It is an advantage if the WUR can distinguish between the wake up signal and the unwanted signal, before the microcontroller.
    b) Addressing Capability
    For added flexibility, the WUR should be able to receive some type of address or other MAC message in addition to the wake-up signal, in a form of wake up packet. This is another level of qualifying the wake up, and directing it towards a specific device.
3) *Flexibility and Usability*
    a) Antenna and Frequency Re-use
    Because of size and hardware limitations, the WUR circuit should be easily integrated with the existing circuit.
    b) Use Existing Transmitter
    If possible, wake up signals should be sent using the existing transmitter used in the network.

Trying to satisfy all of these requirements with low power consumption is not trivial - especially in a WBAN, where many high power wireless transmitters can be located in the immediate vicinity of a WBAN. The communication among active devices will also affect the WUR of a sleeping node and should not generate false wake-up signals.

IV. DESIGN AND IMPLEMENTATION

The Network Co-ordinator broadcasts a wake-up signal and packet. This signal should be sensed by all sensors in the

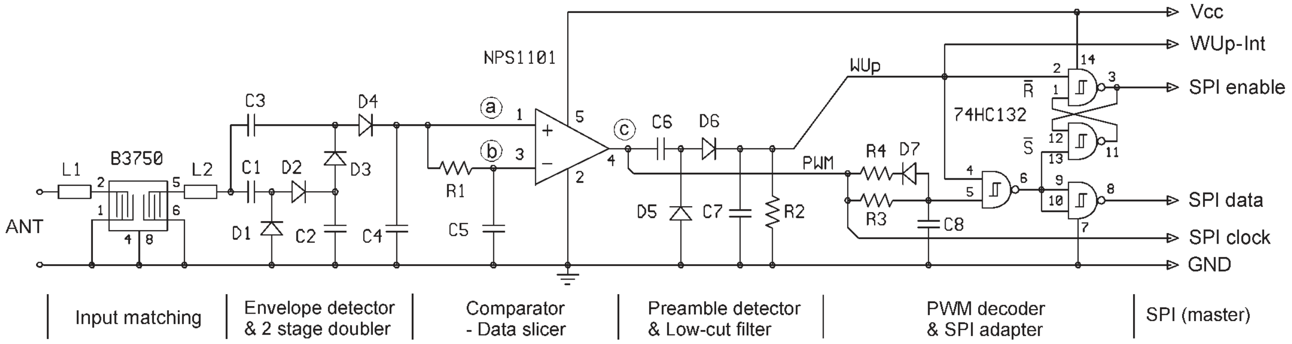

Fig. 3. Wake Up Receiver Circuit

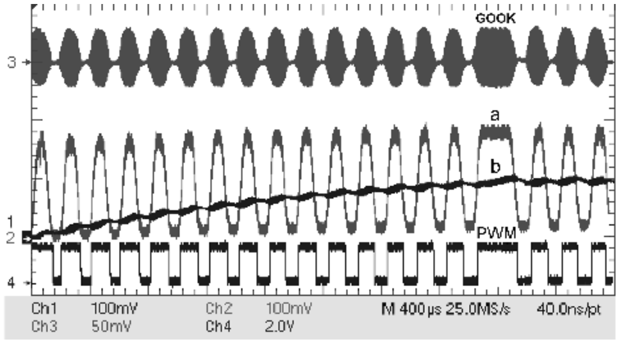

Fig. 4. Input signals. (a) - Output from the envelope detector. (b) - Adaptive threshold. (GOOK) - GOOK modulated signal. (PWM) - Output from the comparator

Network. They read the packet and only the sensor targeted by the wake-up packet turns on its main transceiver. It then either sends a data packet or waits for a certain time to receive additional commands.

The wake-up packet consists of a preamble sequence which triggers the wake up event (WUp-Int), followed by a payload which addresses the sensor that needs to be woken up. The packet contains extra commands and instructions (requirement 2.b). This packet is transmitted using OOK modulation. We use passive components to construct a low cost WUR with very low power consumption to meet requirement 1.a.

A block diagram of the WUR presented in this paper can be seen in Fig.1. A charge pump (two-stage voltage doubler-multiplier) is used as an OOK signal envelope detector. Then, the correct bit sequence for the received packet is formed using the data slicer (comparator). The comparator threshold is adaptive, rather than constant, and it is determined by the strength of the received signal. A Preamble Detector triggers the wake up interrupt if the preamble is in the expected OOK datarate range. The next part of the circuit is the Pulse-Width Modulation (PWM) decoder and the SPI adapter. This part of the circuit first decodes the PWM encoded signal and generates SPI compatible signals for data transfer to the processor.

A. Envelope Detector and Data Slicer

A schematic of the WUR is shown in Fig.3. The first part of the circuit is the envelope detector - a two-stage doubler (C1-C4, D1-D4). It extracts the envelope of the received GOOK signal (tracks the received signal power). Resulting signal is shown in Fig.4, signal ‘a’.

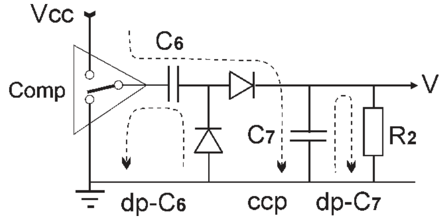

Fig. 5. Preamble detector. ccp - common charge path for C6 and C7. dp - discharge paths

The next part of the circuit (R1, C5) is used for adaptive threshold generation (Fig.4, signal ‘b’). The adaptive threshold mechanism has two advantages:

1) The threshold value for the comparator is always held at 50% of the ‘a’ signal level, according to received signal power. This is used to increase the dynamic range of the WUR, for both weak and strong signals. It maintains good mark space ratio (Fig.4, signal ‘PWM’), regardless of whether the received signal is weak or strong or GOOK modulated. (GOOK modulation is OOK modulation with non-sharp transitions.)
2) The energy from the antenna is used for the threshold generation, instead of a voltage divider, therefore static power is reduced.

B. Preamble Detector and Wake Up Signal Generator

The next part of the circuit (R2, C6, C7, D5, D6) is used to generate a wake up interrupt from the preamble. The preamble is an OOK signal of higher frequency than 2kHz in our implementation (Fig.4 and Fig.6). This preamble is used for two purposes:

1) Sets the threshold signal (‘b’) to the mid-level of the envelope detector signal (‘a’), Fig.4.
2) Significantly reduces interference from other communications. Only the OOK modulated preamble of higher than predetermined data-rate will raise the WUp-Int signal enough to trigger an interrupt. Lower data rate OOK signals do not trigger interrupts.

On the first rising edge at the comparator’s output, capacitors C6 and C7 are partially charged with the same amount of charge. (Fig.5, common charge path-ccp). The voltage on the C7 is then $V_{C7} = V_{cc}C_6/(C_7 + C_6)$. On the falling edge, C6 gets instantly discharged through the diode (Fig.5, dp-C6), and C7 gets slowly discharged through R2 (dp-C7), until

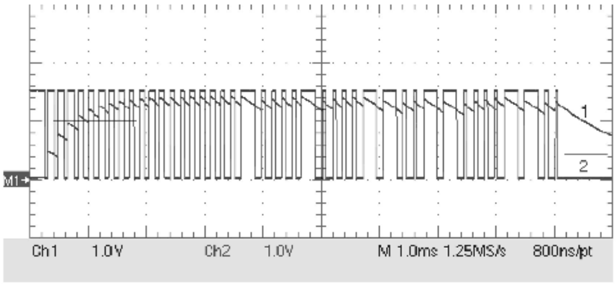

Fig. 6. Wake up packet detection. Preamble detector's input (PWM signal 2) and output (WUp signal 1). WUp reaches the WUp interrupt threshold.

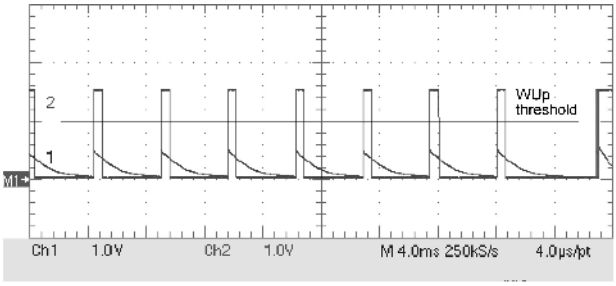

Fig. 7. WUp in case of a GSM call (without input RF filtering). Preamble detector's input (PWM signal 2) and output (WUp signal 1). WUp does not reach interrupt threshold.

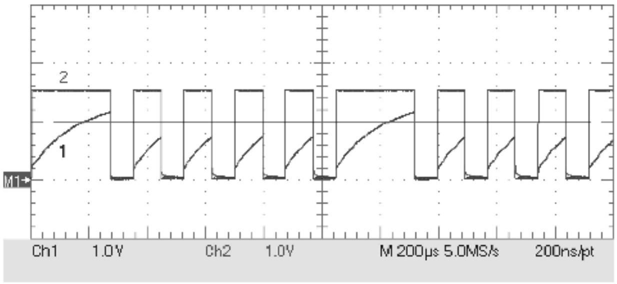

Fig. 8. PWM signal as decoder's input (2) and output (1). Schmitt trigger high level is also noted

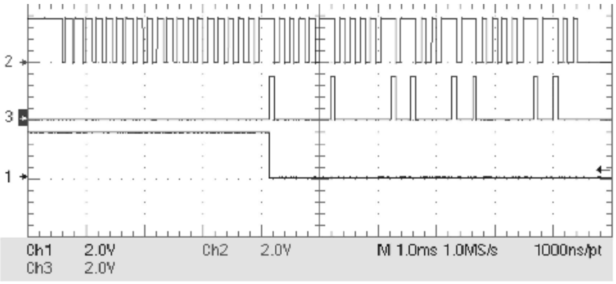

Fig. 9. Generated SPI signals from the Wake Up Packet. Ch2 - input to PWM decoder & SPI adapter, used as a SPI clock. Ch1 - SPI enable and Ch3 - SPI data

the next rising edge. For a low rate of rising edges (low OOK data rate), C7 is completely discharged, and V_{C7} never reaches the interrupt threshold. For higher frequencies C7 is gradually charged, and eventually reaches the threshold. For the implemented WUR, an OOK data rate of about $2\mathrm{kHz}$ is needed to reach the Schmitt trigger level (0.66Vcc) as an interrupt. Changing the C7/C6 ratio and the R2C7 time constant changes this frequency. The wake up packet preamble raises this WUp-Int to generate the interrupt, as illustrated in Fig.6. On the other hand, the signal from a GSM mobile phone during a call does not trigger an interrupt, as illustrated in Fig.7. This figure shows how our WUR, without any RF filtering at the input, interprets a signal from a GSM mobile phone during a call. Note that the whole FSK modulated packet of data is seen as a high level impulse once it is OOK demodulated. The width of these impulses is $0.6\mathrm{ms}$ and they arrive at the frequency of $215\mathrm{Hz}$.

This preamble detector drastically reduces false wake up interrupts caused by spurious wireless FSK transmissions in the vicinity of a WBAN (particularly from GSM systems which are the strongest and most common).

C. PWM decoder and SPI adapter

The next part of the circuit (R3, R4, C8, D7 and 74HC132 Quad 2-input NAND Schmitt trigger) is used to decode the PWM signal and make it SPI compatible. First, the PWM signal is filtered using R3-C8, where only longer pulses (logical "1") can raise input 5 of the 74HC132 to the Schmitt "1" level (Fig.8). This value (R3-C8) is data-rate dependant and should be changed if another data rate is used. The rest of the logic is used to generate the SPI data and SPI enable signals (Fig.9, channel 1 and 3). A high level of the WUp signal is needed to generate SPI data. An SPI enable signal is generated when the first bit in the packet arrives. This bit has to be "1" (start bit). Then, the SPI data is the PWM filtered signal (Fig.10, middle signal), and the SPI clock is the raw PWM signal after the comparator (Fig.10, top signal). The WUR acts as a SPI master.

V. WUR CHARACTERISTICS

We implemented a fully working prototype of the WUR, using surface-mount devices (SMDs). Two tests were conducted on this prototype. The wireless data transmission test was performed using the ADF7020 transceiver, for the receiver validation and power consumption measurements. Testing of the WUR is done at the Industrial, Scientific and Medical band (ISM) carrier frequency of $433.92\mathrm{MHz}$, using the transceiver's GOOK mode. The output transmit power was $10\mathrm{dBm}$. Frequency/data rate/rejection characteristics were measured using RF generators.

A. Frequency, Sensitivity and Data Rate

The working frequency is determined by the type of zero bias diode. If used with the presented zero bias Schottky detector diodes [14], the WUR can be suited to work at any frequency up to $1.5\mathrm{GHz}$, without much change in the sensitivity. For higher frequencies, different types of diodes should be used. Our prototype was built for the 433MHz ISM band. For the medical WBAN employment, this WUR could be modified to work on a less-crowded band, or a special medical band.

The Receiver sensitivity/data rate characteristic is determined by the RF characteristic of the Schottky diode, the OOK data-rate and the threshold level of the comparator-data slicer. We used the 100% AM test method for sensitivity measurement, with DC balanced data. This architecture is capable of working at data rates up to $80\mathrm{kbit/s}$, with proper

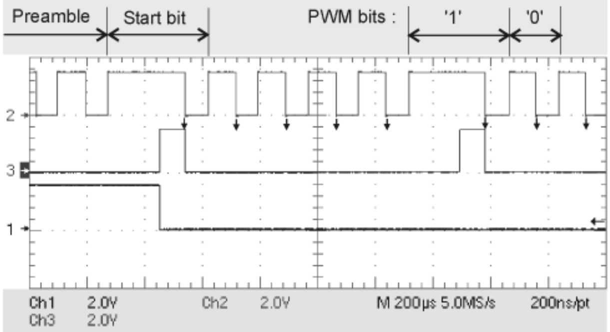

Fig. 10. Zoomed SPI signals from Fig.9. First data bit (PWM bit "1") is the Start bit (synchronisation bit)

changes in the component values for preamble detector/SPI adapter. The sensitivities are:

Data Rate (kbit/s)	1	2	5.5	10	30	50	80
Sensitivity (dBm)	-52.1	-51.4	-51	-46	-40	-36	-30

If input RF filtering is used (narrowband Surface Acoustic Wave (SAW) filter), input sensitivity is decreased by $3\mathrm{dBm}$ due to the filter losses.

At higher data-rates, the comparator needs a higher voltage difference at the input to reduce the propagation time. Therefore we can see the reduction in the sensitivity. A sensitivity of $-51\mathrm{dBm}$ (or $-48\mathrm{dBm}$ with SAW filtering) for $5.5\mathrm{kbit/s}$ data rate, satisfies the requirements of WBAN where the communication range is several meters. For the transmitter's output power of $10\mathrm{dBm}$, using the whip antennas ($0\mathrm{dBi}$) we attained more than $10\mathrm{m}$ indoor range.

B. Interference Rejection

If there is a high power transmitter in the vicinity of a WUR, the envelope detector will detect the transmitted carrier wave. Around a WBAN, the most common high-power transmitter is the GSM phone. Its output power levels can reach up to $+33\mathrm{dBm}$ during a call. Any low power WUR based on the envelope detection method will be affected by these signals, if there is no filtering at the input, as it is shown in Fig.7. In this figure, we show the comparator's output, without input RF filtering, for a nearby phone during a call. Other common interferers will not be as critical as GSM, since their output power levels are not as high, and most of the WUR do not have great sensitivity. From an overall power consumption perspective (Requirement 1. b.) it is very important how the receiver deals with these interferences. If the WUR generates a wake up interrupt every time there is a packet being sent from some device, this would lead to high power consumption. Our WUR has the preamble detector to filter the most common interferences around a WBAN from generating a wake up interrupt, as explained earlier.

These interferences do not generate false wake up interrupts, but the communication can be interrupted if the interference happens during the transmission of the wake up packet, leading to corrupt data and packet dismissal after the cyclic redundancy check (CRC). This scenario occurs during a GSM call if no RF filtering is used. Therefore, in order to reduce the Packet Error Ratio, we placed a SAW filter at the input. Interference rejection performance is measured by applying a desired signal of power level D, along with an undesired (i.e. interfering) pulse signal of power I, injected into the RF input of the receiver. Undesired signal power is adjusted until the corruption happens in the signal at the output of the data slicer. The interference rejection performance is expressed as the ratio of the power of the desired signal and the power of the undesired signal ($\mathrm{D/I}$) at this threshold. Fig.11 shows the lowest possible $\mathrm{D/I}$ for the acceptable mark/space ratio during the interference pulse. We performed the measurements for the desired OOK signal with data rate of $5.5\mathrm{kbit/s}$ at the working frequency of $433.92\mathrm{MHz}$ and the power of $-45\mathrm{dBm}$ ($3\mathrm{dB}$ higher than the sensitivity). For the GSM 900 band, the rejection is approx. $55\mathrm{dB}$. For frequencies higher than $1.5\mathrm{GHz}$, the rejection becomes very high because of the diode characteristics.

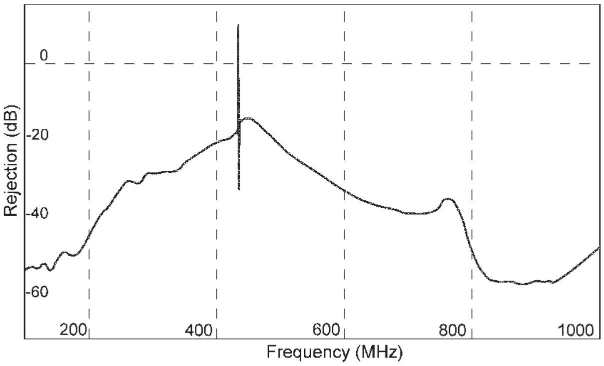

Fig. 11. Interference rejection. Measurement is done for the signal at 433.92MHz with -45dBm power (100% AM).

Interferers in the $433\mathrm{MHz}$ ISM band will continue to cause toggling and data corruption if the signals are strong enough. However, strong transmitters in this band are not as frequent around a WBAN as a GSM phone. For example, an ISM433 key fob in the WBAN area can cause sporadic interference, although this will be far less common than a GSM phone. For medical environments, a dedicated frequency bands may need to be used.

C. Communication and Interface

Most of the WURs use the standard coding schemes such as Manchester, PWM (Pulse Width Modulation) and PIE (Pulse Interval Encoding). Manchester decoding requires a clock recovery circuit that uses a local oscillator or a phase locked loop. These circuits are more power hungry; therefore, decoding consumes more energy. We use the PWM method for communication in order to have very low power clock/data extraction and conversion to SPI compatible interface.

The wake up packet is made of Preamble, Synchronisation bit, Data and CRC. The preamble is used to generate the wake up interrupt. The synchronisation bit is used to delimit the start of the message, and generate the SPI enable signal, for the microcontroller to start reading data. The data should be an address and/or some command defined by the MAC protocol, and the packet should also contain a CRC.

D. Power Consumption

The static power consumption of the WUR is determined by the static power consumption of the comparator and the CMOS logic for the SPI. For this implementation, we used the NPS1101 CMOS comparator by NanoPower Solutions, Inc. [15] as the comparator with the lowest power consumption available on the market. Measurements show that the static current consumption of our WUR, based on NPS1101 comparator is $180\mathrm{nA}$ at $1.5\mathrm{V}$. This figure is for the complete circuit including the SPI adapter based on HCMOS technology, for which the quiescent current is low (few nA at $25°\mathrm{C}$). Therefore, the static power consumption (when listening on a channel) is $270\mathrm{nW}$.

The dynamic power when receiving an OOK packet is dissipated on the preamble detector capacitances and the SPI adapter CMOS inputs. It is determined by the values of the capacitors C6, C7 and C8, power-dissipation capacitance of the NAND gates $\mathrm{C_{pd}}$, and the data rate. The total measured energy per bit (Data slicer + Preamble detector + PWM decoder + SPI adapter) is $1.75\mathrm{nJ/bit}$. This does not vary much with the data rate, because higher data rates would have higher dynamic power consumption but lower time per bit, and vice-versa for the lower data rates. The average dynamic power dissipation is $\mathrm{P_{dyn} = f \times V_{cc}^2 \times C_{sum}}$. The energy per bit is then $\mathrm{E_b = P_{dyn}/f = V_{cc}^2 \times C_{sum}}$. (f is the data rate and $\mathrm{C_{sum}}$ is the sum of the external capacitances and power-dissipation capacitance of the SPI adapter). Therefore, E_b is data rate independent.

E. The Effect on the Overall Power Consumption

We will consider a sensor with the architecture as in Fig.1. MSP430 will dedicate an SPI port for receiving the wake up packet, and an interrupt pin for receiving the wake up signal. The advantage of using this method compared to using general input/output pins (GPIO), for communication with the wake-up receiver is that it leads to easier application development and gives lower power consumption. Namely, the MSP430 can stay in its lowest power shut down mode (LPM4.5), consuming only $100\mathrm{nA}$, while waiting for the wake up signal. After getting a signal, it does not have to go into active mode, but can switch into LPM3 if the SPI interface is used, consuming $1.8\mu\mathrm{A}$ during the packet reception, and only if the packet is intended for it, it will go into active mode, switching on the regular receiver.

The component values for the preamble detector and the SPI adapter were set for $5.5\mathrm{kbit/s}$ data rate for communication testing. This is the maximum data rate for the packet format in Fig.6 where the MSP430 has enough time to wake up from LPM4.5 to LPM3 in the time period from Wake up interrupt until SPI enable. This time varies from $2\mathrm{ms}$ to $3\mathrm{ms}$ for the MSP430.

VI. COMPARISONS

The simplest and lowest power consumption wake up circuit was presented in [2]. A zero-power radio-triggered hardware, based on a multiple-stage charge pump, that extracts energy from the radio signals and provides a wake-up signal to the network node without using an internal power supply is presented and simulated. However, there is neither RF filtering nor an addressing mechanism nor selectivity of the wake-up signals. It means that every nearby RF activity can trigger a wake up interrupt for the receiver. This would lead to higher overall power consumption since the microcontroller and the regular receiver have to be woken up every time to decide if the wake up was intended for the sensor. Also, there is no addressing mechanism. Therefore, for each wake-up signal, every sensor in the vicinity switches on the transceiver, consuming energy to test if the signal is meant for it. A similar solution based on a MOSFET with a sensitivity of $-29\mathrm{dBm}$ and a current consumption of $2.6\ \mu\mathrm{A}$ is presented in [3]. Semi-passive RFID wakeup solutions fall within this group too. A wake up circuit with high sensitivity ($-65\mathrm{dBm}$), and with static power consumption of $4.8\ \mu\mathrm{W}$ is presented in [7].

In the WBAN, there is significant interference from the various wireless devices found in the vicinity, and there will be numerous sensors. For example, as these wake up circuits usually do not have filtering, a simple call from a nearby mobile phone would generate 215 false wake up interrupts per second for the whole duration of a call, causing unnecessary waking up of the sensor. Therefore, a more sophisticated WUR, with addressing capabilities and interference rejection is needed.

A low power wake up receiver that has addressing capabilities and is closest to our implementation regarding the power consumption is presented in [8]. A simple protocol for wake-up signal transmission and a WUR that includes a charge pump and a digital comparator is presented. This signal is read by the microcontroller where it is decoded and analysed in active mode (consuming high current), which can happen on any interference. This increases the effect on the whole sensor power consumption (requirement 1.b). Therefore it is not as power efficient if there is need for frequent wakeups or if there is interference in a channel. The dynamic power was not given or considered in the paper. Additionally, the comparator has a fixed (high) threshold level, compared to our adaptable threshold; therefore sensitivity and dynamic range is reduced.

A different solution based on an envelope detector and a programmable amplifier is shown in [9]. It has a dedicated FPGA for digital decoding and preamble detection. The data is transmitted serially and it has no standardised connection. The static power consumption of $12.5\ \mu\mathrm{W}$ and sensitivity/data rate of $-57\ \mathrm{dBm}$ and $100\ \mathrm{kb/s}$ are reported. A similar solution with an envelope detector and amplifier is reported in [13]. It has a power consumption of $96\ \mu\mathrm{W}$, and does not have wake up signal decoding. The design requires an active microcontroller with constant analog to digital conversion (ADC) to do the signal decoding, which further increases the power consumption.

Finally, [11] presents a high sensitivity ($-72\ \mathrm{dBm}$) solution and good ($0.5\mathrm{nJ/bit}$) dynamic power consumption, but it has a static power consumption of $52\ \mu\mathrm{W}$. It is mainly targeted for Wireless Sensor Networks with higher ranges than WBAN, and higher power consumption requirements.

Table I presents a comparison of our receiver with low power wake up receivers with addressing mechanism both realised and tested [8], [9], [13] and [11] or simulated in detail

TABLE I
WAKE UP RECEIVER COMPARISONS

	Detector power†	Decoder power†	Testing Frequency	Data Rate	Sensitivity	Interference filtering
This work	0.27 μW @ 1.5V	8 nW	433.92 MHz	2 to 80 kb/s	−51 dBm	Preamble detector (+SAW filter)
Ansari [8]	2.6 μW @ 3V	μC dependent	869 MHz	0.75 kb/s	N/A	Microcontroller
Durante [9]	12.5 μW @ 1.5V	5 μW	2.4 GHz	100 kb/s	−57 dBm	FPGA
Pletcher [11]	52 μW @ 0.5V	N/A	2 GHz	100 to 200 kb/s	−72 dBm	BAW resonator
Doorn [13]	96 μW @ 1.5V	50 μW	868 MHz	0.862 kb/s	−51 dBm	SAW
Le-Huy [10]	17.8 μW* @ 3V	0.8 μW*	2.4 GHz*	50 kb/s*	−53 dBm*	None
Takiguchi [12]	12.4 μW	N/A	950 MHz*	40 kb/s*	N/A	Bloom Filter

* - Simulated values; † - Static power consumption (When in listening mode)

[10] and [12]. All values given in the table are extracted from the referenced papers, and no assumptions were made. All of these wake up receivers have higher power consumption than our WUR. Some of them have better sensitivity or data rate, but none of them is as well-suited for WBAN as the WUR presented here. We compared only the static power consumption, since most of the compared works do not have a detailed analysis of dynamic power consumption and energy per bit.

VII. CONCLUSION

We presented a novel WUR architecture suitable for WBAN applications. We measured the performance of this receiver, implemented in the ISM 433MHz band and compared the results with other state of the art designs. The measured results show that our radio is the lowest power solution that has receiver capabilities, exhibiting listening power consumption 10 to 100 times lower than other wake up receivers. This, along with the good sensitivity and flexibility to change the receiver's circuit values to work with different frequencies and data rates, makes the proposed WUR a very good choice for WBAN application, where low power consumption is an essential attribute. The methods used in this paper can also be adapted to other short range Wireless Sensor Network topologies where power consumption is of prime concern.

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