Ultra-Low Power Wake-Up Receiver for Location Aware Objects Operating with UWB

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***Abstract*—Ultra-wide band is one of the most promising localization technologies already and increasingly used in industrial environments. It is also starting to be included in many Internet of Things and mobile devices. The most attractive feature of ultra-wide band for localization and positioning is the achievable centimeter-accuracy that can enable a highly secure spoofing-protected application. On the other hand, the main drawback that still limits its use in battery-operated devices is the high power consumption, especially in idle listening. Today most common approaches use duty cycling, which reduces the overall power consumption at the cost of increased latency. The paper presents a hardware wake-up radio with addressing capability for ultra-wide band communication and ranging. Moreover, the paper introduces a novel protocol that enables the generation of wake-up signals directly with any existing ultra-wide band transceiver, without the requirement of a different radio. The proposed solution achieves $-48\,\mathrm{dBm}$ of sensitivity with only $100\,\mu\mathrm{W}$ of power consumption. The proposed system enables full asynchronous communication, achieving millisecond latency and always-on capability. Experimental evaluation with a popular commercial transceiver produced by Decawave demonstrates the high energy saving and the effectiveness of the proposed addressing protocol by reducing energy consumption in the order of 100x compared to conventional receivers.**

***Index Terms*—WUR, UWB, low-power, ultra-wide band, IoT, Wireless Networks**

I. Introduction

In the last years, the broad proliferation of smartphones and ultra-low power wireless devices has paved the way for a wide range of new and innovative services, including indoor localization, positioning information, and contact tracing [1], all based on Radio-Frequency (RF) positioning systems. These allow to obtain a device or user-relative location in an indoor or GPS-denied environment, or simply a point-to-point distance between two objects. Indoor localization can enable multiple features in many consolidated systems such as smart architecture (smart cities, smart buildings, smart grids [2], [3]) and Machine Type Communication (MTC) [4]. Among various technologies that exploit radio communication for localization and positioning such as BTLE (Bluetooth Low Energy), WiFi and RFID [5], Ultra-Wide Band (UWB) is the technology [6] that best fits requirements in terms of localization accuracy; however, the commercial availability of integrated transceivers still lacks ultra-low power solutions. To give an example, the world leader of the market, Decawave DW1000[1], requires almost $0.4\,\mathrm{W}$ during ranging procedures and more than $0.3\,\mathrm{W}$ to identify eventual transmissions. This power consumption is the main drawback that significantly limits the use of UWB in battery-operated devices of the Internet of things (IoT). Indeed, in a typical battery-operated IoT device, the radio transceiver is the most power-hungry component; therefore, the energy efficiency of the communication heavily impacts the average time the battery of these devices can last.

Many techniques proposed in previous works, such as [7]–[9], have been used to demonstrate that aggressive duty cycling, switching between a power-hungry reception period and a low power sleep interval, significantly improves the lifetime of the device [7]. However, the duty cycling mechanism still has two side effects: the listening power consumption is not totally removed and the transceiver is likely to miss incoming messages. Although currently the research and commercial spotlight is on emerging technologies related to long-range and wide-band machine-to-machine communications, existing solutions do not satisfy localization demands with regard to average power consumption and accuracy. Indeed, the transceiver needs to check the medium periodically. This leads to an intrinsic trade-off between latency and power consumption [10], as the latency is inversely proportional to the off-time of the radio and energy savings. In fact, the longer the radio turn-off period, the more energy is saved, but the latency will be higher. A recent approach exploits asynchronous communication to overcome the latency/power trade-off, and it is considered one of the most efficient mechanisms for battery-supplied sensor nodes [11]. This is the approach that is making it possible to create novel always-on nano-power WUR (Wake-Up Radio) receivers [10], decreasing the idle-listening energy and achieving low latency communication, an essential factor in frameworks where devices need to estimate a point-to-point distance in real-time.

Industrial and academic researchers are investigating different methodologies to decrease the energy used by UWB transceivers in idle periods. However, most of them are either proposing custom solutions specifically designed and optimized for a limited number of application scenarios [12], or

[1] www.decawave.com/product/dw1000-radio-ic/

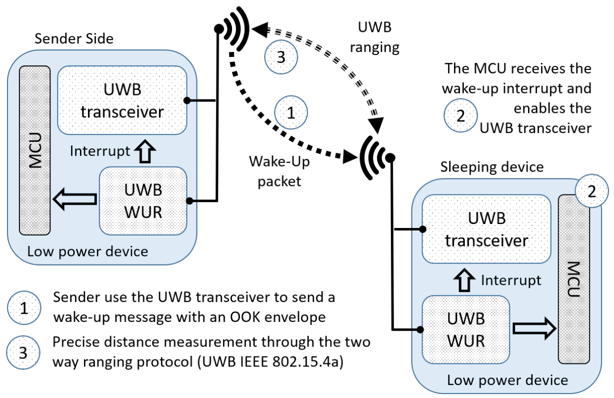

Fig. 1. System overview and functional description.

support ultra-constrained UWB tags with near zero on-board capabilities [13], or, more often, utilize duty cycled active listening periods [7], [8], [14].

This paper presents a flexible and programmable WUR system comprised of a custom low power hardware design and a UWB protocol to generate wake-up signals with commercial UWB transceivers. The hardware design exploits off-the-shelf components for a fast proof-of-concept deployment and enables a *first-of-this-kind* asynchronous triggering for ultra-low power distance estimation among wearable and IoT devices. The overall power consumption of the designed wake-up radio is only $100\,\mu\mathrm{W}$ achieving a sensitivity of up to $-48\,\mathrm{dBm}$ at $3.9936\,\mathrm{GHz}$. The proposed protocol allows every generic UWB transceiver to generate wake-up signals with addressing capability. It also includes a practical discussion and evaluation using the market reference Decawave DW1000 UWB transceiver and our ultra-low-power WUR tuned for multi-GHz radio channels. Finally, the paper demonstrates that our solution can decrease the average power consumption by up to $4000\,\times$ compared to a continuous listening mode, and up to $40\,\times$ if we consider a $1\,\%$ duty cycled approach with an average latency of $15\,\mathrm{s}$. Despite the proposed application scenario focusing only on localization, the proposed system can be used in a large set of use cases, such as low power wireless communication [7], detecting human presence [15], and in the area of road safety [16]. Fig. 1 shows the system functional overview considering two ultra-low-power battery supplied devices, each of which is equipped with a commercial UWB transceiver and our always-on radio receiver. Depending on the application scenario and the device role, they can query each other for a distance measurement by sending a wake-up message (*(1)* - Fig. 1) to trigger the standard two way ranging protocol [17] (*(3)* - Fig. 1). In Fig. 1, the only active component in the sleeping device is the UWB-WUR, which triggers the MCU (Micro-Controller Unit) (*(2)* - Fig. 1) upon a correct reception of the wake-up message. On the other side, the sender device relies only upon an UWB transceiver to localize and to turn on other devices from deep-sleep mode.

II. Related Works

In IoT environments, radio transmission and reception dominates the power consumption of the vast amount of battery-operated devices, motivating researchers and industry to develop new technologies capable of reducing the energy footprint of the transmitters and receivers [18]. In most applications, the radio power consumption far exceeds that of sensing and processing, often becoming the main bottleneck in extending device lifetime [10]. Reducing the power consumption when receivers are idle is one of the most crucial challenges [19]. Today, most common approaches make use of low-power radios and duty-cycling [20] Medium Access Control (MAC) protocols. Recent works have demonstrated the more effective technique of switching off the main receiver, then introducing new wake-up circuitry capable of detecting incoming transmissions [11], [19]. During duty-cycling (DC), devices periodically switch off the radio and wake up only to transmit or receive. Unfortunately, the active period cannot be arbitrarily low due its inverse proportionality with latency and minimum packet transmission time. Indeed, the reception window must be large enough to capture the incoming packet preamble, a condition that limits the lower bound of the DC ratio [10]. The introduction of a WUR with orders of magnitude lower power consumption, usually in the order of micro or nano watts, allows the design of ultra-low power devices with asynchronous and always-on listening capabilities [9], [10], [19], [21]. In addition, some WURs include circuitry for an addressing mechanism that can be used to wake-up only a specific node rather than the entire system [22]. In recent years, many WUR solutions have been presented and evaluated [19]. They commonly rely on discrete components [10] and custom-ICs [23], and sometimes a hybrid implementation between the two [12], [13]. All the previous works have demonstrated the benefits of wake-up radio, and the vast advantages over duty cycling. However, designing low-power wake-up radios is still challenging and includes some trade-offs [11], [24]. Most common solutions in previous works are based on custom sub-GHz hardware exploiting OOK (On-Off Keying) and ASK/FSK (Amplitude-Shift Keying/ Frequency-Shift Keying) modulations [19]. Also the $2.4\,\mathrm{GHz}$ channel is often used [25], [26]. On the other hand, only a few solutions have exploited bands above $5\,\mathrm{GHz}$, such as [27] and [28], working respectively at $5.8\,\mathrm{GHz}$ and $60\,\mathrm{GHz}$.

The work presented in [10] is the state-of-the-art regarding discrete components WUR receivers, achieving a sensitivity below $-50\,\mathrm{dBm}$ and a power consumption of $1.3\,\mu\mathrm{W}$. However, it is optimized explicitly for OOK modulation in the $868\,\mathrm{MHz}$ band. Other publications, such as [29] and [12], proposed micro-power transceivers improving upon the basic capabilities of [10]. They combine radio energy harvesting and UHF always-on receivers to enable indoor localization [12] or wireless body area networks [29] (WBANs). The latter exploits a combination of wake-up receiver and impulse radio ultra-wide band (IR-UWB) technique to enable localization

TABLE I
COMPARISON WITH STATE-OF-THE-ART WURS

Reference	Band	WUR Power	Technology
[10]	868 MHz	1.3 µW	OOK
[12]	868 MHz	3.88 µW	dual-radio (UWB and OOK)
[29]	400 MHz	44 µW	dual-radio (UWB and OOK)
[30]	868 MHz	1.83 µW	dual-radio (LoRa and OOK)
[28]	60 GHz	230 µW	4-path phase-array
[31]	433 MHz	1.3 µW	dual-radio (5G and OOK)
[32]	2.4 GHz	470 µW	WiFi
[8]	3.99 GHz	-	Duty Cycle
[7]	3.99 GHz	-	Duty Cycle
this paper	3.99 GHz	100 µW	**UWB**

and low-power data transmission. In [30], authors combine the capabilities of a micro-watt WUR to enable pure asynchronous communication while keeping the long-range connectivity feature of LoRa. They demonstrate data reliability of 100 % and a round-trip latency in the order of milliseconds with less than 46 mJ and 1.83 µW sleep mode power consumption. The authors of [31] proposed the first WUR mixing 5G radio technology and a custom 433 MHz OOK modulation. Their WUR device features an energy consumption of 390 mJ and a response time of 95 ms for decoding a wake-up signal Results in [28] represent the reference for high-frequency WURs, they reached a band of 60 GHz using 230 µW. The radio front-end is based on four parallel channels. Lastly, [8] and [7] proposed UWB ultra-low power sensor node exploiting the low power listening mode of the DW1000. However, they have a high latency (>10 s) or require the usage of predefined transmission windows.

In contrast with previous works, shown in Table I, the goal of this paper is to enable asynchronous and always-on communication exploiting only commercial UWB transceivers. We demonstrate the practical feasibility by describing the entire system, from the UWB power transmission to the OOK modulation and the hardware design. In contrast with previous works [8], [12], [28], our system is easily integrable in a wide span of different applications. Moreover, to the best of our knowledge, this is the first complete system description that enables ultra-low power distance estimation using only the UWB radio and commercial transceivers.

III. ULTRA-WIDE BAND COMMUNICATION

The goal of this paper is to design a new asynchronous micro-power receiver for location-aware IoT devices, using signals with an extremely high fractional band (more than 20%) or having a bandwidth greater than 500 MHz. Hence the signal is considered to be placed in the unlicensed spectrum between 3.1 GHz and 10.6 GHz provided by the Federal Communication Commission (FCC) for wireless protocols concerning communication and distance measurements. As regulated by the IEEE 802.15.4-2020 standard, the ultra-narrow electromagnetic impulse for the unlicensed spectrum has a 2 ns time width, a value proportional to the 499.2 MHz bandwidth (BW). For clarity and conciseness, in this paper a

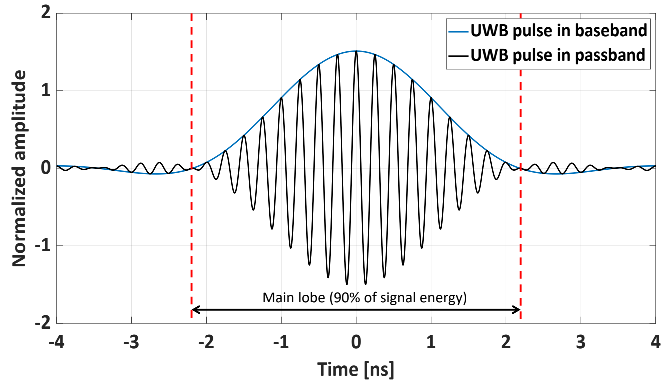

Fig. 2. Reference UWB pulse considered for simulation, voltage normalized for a maximum power spectral density of 1 dBm/MHz

single default carrier frequency of 3.9936 GHz is considered among all the possible settings. The IEEE 802.15.4-2020 physical layer describes the impulse time width, phase and magnitude, and the power spectrum limitation of the UWB envelope. The carrier-based impulse generates three different symbols basing on phase and magnitude: +1 or -1, and 0. A Zero symbol is the absence of the impulse in a specific time slot, while the carrier phase discriminates the impulse polarity. Those attributes are then used to generate a code-based modulation by the upper IEEE 802.15.4-2020 layers. An example of a normalized impulse following the described rules is shown in Fig. 2. Regarding the power spectrum, FCC limits emissions for UWB transmitters at $-41.3\,\mathrm{dBm/MHz}$ applying two different rules, the maximum mean Power Spectral Density (PSD) and the single impulse maximum power. The first rule imposes a limitation of $-41.3\,\mathrm{dBm/MHz}$ for the radiated power averaged over 1 ms within the given bandwidth, i.e., 74 nW per MHz, while the second limits the signal to 0 dBm when considering a bandwidth of 50 MHz. The first rule heavily affects the peak power compared with narrow-band modulation, such as ISM 868 MHz (Industrial, Scientific, Medical) and WiFi or Bluetooth Low Energy in the 2.4 GHz spectrum, resulting in a 13,500 × reduction compared to these protocols. UWB overcomes this limitation by spreading the signal on a very large bandwidth, with an aggregated average power of 37 µW, obtained by multiplying the bandwidth with the maximum spectral density. However, 37 µW averaged over one millisecond is still one order of magnitude lower than other commercial short-range radio technologies. Moreover, the intrinsic narrow-band structure of the presented WUR does not benefit from the spread energy of a 500 MHz bandwidth when working as an OOK demodulator, limiting the effective collected energy. The second rule limits the instantaneous pulse peak to a 0 dBm threshold. However, considering the physical construction of a single impulse, with 2 ns period, it *de facto* cannot improve the communication distance with our OOK demodulator, which intrinsically integrates the received power over a bit-period. For a baud rate in the range of 1-

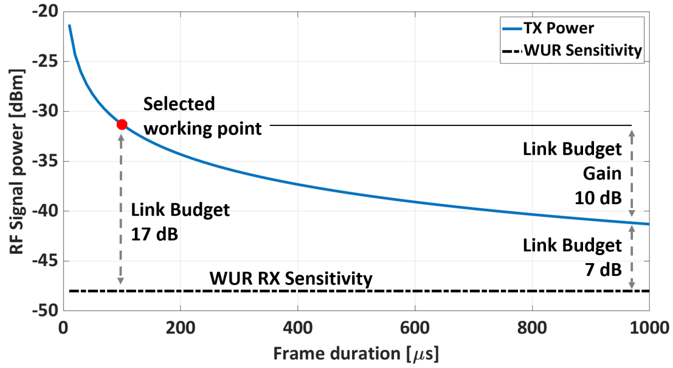

Fig. 3. Relationship between frame duration and maximum transmission power. The red star represents the selected configuration, while the link budget is expressed as the ratio between the average frame transmitted power and the WUR sensitivity at 3.9936 GHz.

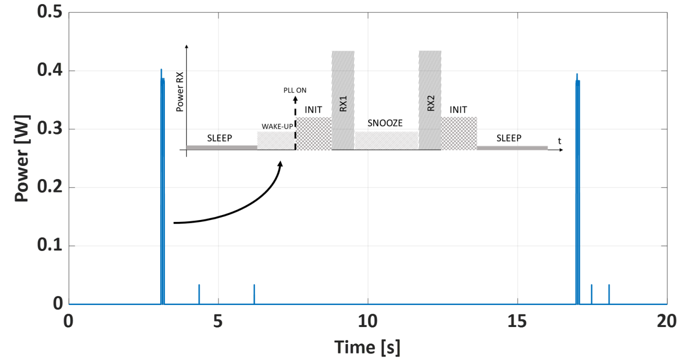

Fig. 4. DW1000 power consumption in LPL listening mode at 1 % DC. A detail shows the receiver operations: RX windows separated by a short SNOOZE interval, INT configuration and PLL synchronization, and the wake-up sequence used to initialize the RF front-end.

10 kHz, the bit-width is in the order of hundreds of microseconds, six orders of magnitude wider than a single UWB pulse.

Considering the average sampling window of 1 ms, the transmitted frame duration setting allows additional transmit power in certain circumstances. The basic principle relies on using frames shorter than 1 ms, whose transmission power can be increased by a factor depending on the duration of the frame relative to the average sampling window. If only one frame is transmitted every millisecond, then a manual power tuning can be applied[2]. The relation between the frame duration and the additional power is calculated through Eq. 1, where F_t is the transmission frame duration expressed in milliseconds.

$$PowerBoost(\mathrm{dB}) = 10\log_{10}\frac{1\,\mathrm{ms}}{F_t} \tag{1}$$

When Eq. 1 is correctly calculated, the power spectrum density appears the same as if no boost had been applied, providing a significant link budget benefit without overcoming FCC limitations. Fig. 3 shows the trade off between maximum power and the overall frame duration. The maximum communication link budged it is achieved at the minimum frame time-width, which for our OOK envelope detector, it is equal to the maximum supported bitrate, 10 kbps.

IV. DW1000 Considerations for Energy Efficiency

Concerning all DW1000 operation modes, the reception is the most costly one in terms of current consumption. In Mode 3 [17] it draws from the source an average current of 122 mA; on the other hand, the sensor board must continuously listen to the ether, waiting for external incoming devices. It is clear that a constant current of 122 mA is not sustainable for ultra-low power devices, such as wearable sensors, IoT objects and sparsely deployed systems, where the average current drawn from the should be in the order of few micro-watts to reach long term battery operativity.

Aiming to decrease the average power consumption, DW1000 [17] supports an automatic low-power listening (LPL) feature, which applies a duty cycle listening approach composed of two reception windows and a programmable sleep timer. In low-power listening mode, the DW1000 is predominantly in shutdown, waking up periodically in reception for a predefined time. Afterward, the DW1000 returns to the sleep mode for another period if no preamble is detected. The procedure is described in the DW1000 user manual [17]. Fig. 4 shows the LPL power envelope at 1 % DC. Each active period opens two reception windows of 50 ms separated by a short sleep interval (SNOOZE) of 6.5 ms. In addiction, an initial phase is required to start the crystal and synchronize the PLL (Phase-Locked Loop). In total, a listening period requires 156.7 ms. If a preamble is detected, the DW1000 returns back to the normal ranging state, continuous listening mode, enabling two-sided-asymmetric ranging. To wake up the DW1000, the transmitter needs to send sufficient preambles to ensure a non-null probability to hit the short receive window. Essentially, the transmitter has to send ≥ 1 messages for each window time width. In practice, this is done by repeatedly transmitting with a period shorter than the active reception window. On the other hand, the maximum latency is equal to the sleep time.

Considering a low power listening configuration with 1 % duty cycle (DC), the average power consumption is 4 mW with an average latency of 15 s. At 10 % DC the average power consumption is already dominated by the DW1000 reception current, reaching an average value of 41 mW.

V. Wake-Up Radio

In this section, the WUR electrical and functional description is presented; Fig. 5 shows the architecture of the always-on receiver coupled with a commercial UWB transceiver, which can be programmed to act as a wake-up transmitter. It emulates an OOK narrow-band transmitter by generating a specific pattern composed of standard UWB packets. The receiver support only the OOK modulation, the simplest form of ASK modulation in which digital data are represented as the presence or absence of a carrier wave. This design choice

[2] Decawave APS023: APPLICATION NOTE

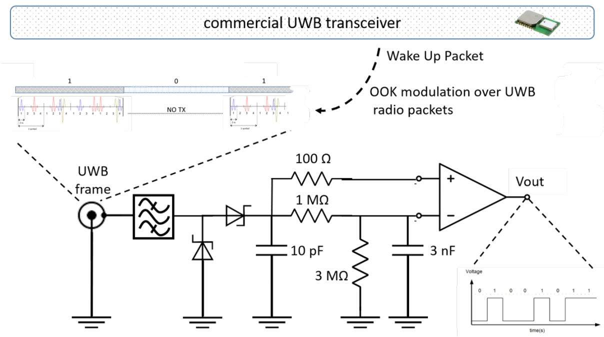

Fig. 5. Wake Up Radio: the receiver schematic and the system overview. Highlighted: The envelope demodulator, the low-pass filter, the comparator and the decoding, all realized with off-the-shelf components.

allows an ultra-simple design that supports low energy consumption and high integration in many different contexts. The radio packet is a signal defined by a specific length (number of bits) sent at a specific bitrate f_p. When the destination address is matched, the preamble detector signals an interrupt to the onboard microcontroller (Fig. 5), which then starts reading data from the pin connected to the output of the comparator. Hence the proposed architecture comprises only four main blocks: a matching network, the passive envelope detector, the interrupt generator, and the address decoder module.

The ultra-low-power envelope detector is on a consolidated schematic, a diode-capacitor power integrator with voltage multiplier capabilities [11], optimized for multi-GHz input spectrum. The detector input impedance can be approximated with a linear curve in the whole $500\,\mathrm{MHz}$ bandwidth, and the maximum matching misalignment reaches a VSWR (Voltage Standing Wave Ratio) equal to 1.2. Low pass filtering and base-band conversion are handled by the voltage doubler stage combined with a high-quality factor ceramic capacitor. The receiver supports OOK (On-Off Keying) modulation, demodulated through the fully passive envelope detector. It is the simplest form of amplitude modulation in which a digital bit is represented as the presence or absence of a carrier wave. The lower spectral efficiency and slower data transfer speeds of the modulation compared to more advanced counterparts are offset by the gains in energy efficiency of the envelope detector and the low bandwidth need. Because our WUR uses OOK modulation, the circuit consists of a passive envelope detector that discards the carrier frequency and its phase, only detecting the amplitude. The WUR demodulator makes use of a single-stage half-wave rectifier with series diodes, the $BAT15-04W$ RF Schottky diode pair from Infineon Technologies, which is optimized for frequencies up to $12\,\mathrm{GHz}$. They offer a sensitivity below $-30\,\mathrm{dBm}$ with the double diode configuration[3]. Once the signal is rectified, the digital bits of the received wake-up address, which follows an 8-bit preamble, are reconstructed by using an ultra-low-power comparator. To be robust against input power changes, the envelope detector includes an adaptive threshold mechanism that keeps the negative input at half of the input signal level. This enforces a limitation on the address compositions, where sequences longer than three ones or three zeros are forbidden. With this approach, the threshold is generated by the energy from the received signal, thus reducing the static power consumption of the circuit as compared to using a voltage divider. This allows to correctly receive a wide range of voltage and power input levels while still retaining a high detection accuracy. For this paper, the LT1017 comparator from Analog Devices has been selected. It features a very low voltage offset below 100 μV and current consumption of 30 μA at $3.3\,\mathrm{V}$. This component can take advantage of the entire working range of the BAT15-04W diode. With this configuration, the WUR receiver features a sensitivity of $-48\,\mathrm{dBm}$ at $3.9936\,\mathrm{GHz}$, the supported bitrate is between $1\,\mathrm{kbps}$ and $10\,\mathrm{kbps}$. The R-C filter tuning of the adaptive threshold mechanism defines the lower limit, while the maximum bitrate is limited by the LT1017 response time measured at the lower-level signal. The last stage of the analog circuit is the preamble detector. To filter interference from noise, thus avoiding false wake-ups, a predetermined preamble that can be detected by this passive part of the circuit (Figure 5) is used before the packet. In this paper, the considered preamble detector is a ultra-low power MCU programmed to decode the received bit-stream. To keep power consumption to a minimum, an 8-bit PIC12LF1552 was selected ($20\,\mathrm{nA}$ in sleep mode). This MCU also allows fast wake-up ($\sim 130\,\mu\mathrm{s}$ at $8\,\mathrm{MHz}$) and operating current of $30\,\mu\mathrm{A/MHz}$

The average power consumption of the WUR receiver is $100\,\mu\mathrm{W}$, which reaches $180\,\mu\mathrm{W}$ during the address decoding. Thus, considering a $10\,\mathrm{kHz}$ streaming, for each reception the WUR needs $500\,\mathrm{nJ}$ in total considering a processing time of $2.4\,\mathrm{ms}$ (t_{beacon}).

VI. WUR Addressing and Protocol

A WUR message includes a specific code and address aiming to wake up only the selected sensor node with as low latency as possible. As the wake-up radio is always on, it can detect and parse the message and generates an interrupt only when the address is correct. An essential contribution of this paper is the proposed protocol that enables every existing commercial UWB radio to generate those messages. For evaluation of our approach, we used the Decawave DW1000 [17], a flexible radio transceiver compliant with IEEE 802.15.4-2020 standard, which is a System on Chip (SoC) embedding a wideband radio front-end. It contains a receiver, a transmitter, and a digital back-end. A serial digital bus interfaces the SoC to the host processor. To enable the aforementioned functionalities, the DW1000 has been configured to operate directly at register level.

Following the goal of using off-the-shelf components, the transmission protocol fits the constraints of the IEEE 802.15.4-2020 standard, making it compatible with most UWB transmitters. Obtaining a reliable OOK modulated signal while complying with these constraints requires a careful calibration

[3]Infineon AN_1807_PL32_1808_132434: APPLICATION NOTE

of the DW1000 settings. For this, it has to be considered that a UWB signal, differently from most narrow-band protocols, is modulated using a combination of amplitude and pulse-position-modulation. This modulation is possible since the wide available band is sufficient to encode a raised-cosine impulse with the main lobe width of few nanoseconds. Specifically, each transmitted symbol is encoded with a predefined amount of multiple orthogonal channel-defined ternary sequences of 31 or 127 chips. Each chip can be either a positive impulse, a negative impulse, or the absence of an impulse. An even distribution of UWB impulses is not allowed under the standard; instead of limiting the range of possible symbol shapes, it can be used as an advantageous feature for the receiver. As an example, one of the determined ternary codes that encode a UWB symbol in the chosen channel is $0000+-00-00-++++0+-+000+0-0++0-$, where $+$ represents a positive impulse, $-$ represents a negative impulse, and 0 represents the absence of an impulse. As can be seen from this ternary code, there is a burst of impulses around the middle of the encoded symbols. This leads to a local increase of the PRF (Pulse Repetition Frequency), which rises from a maximum mean of $62.89\,\mathrm{MHz}$, to a local peak of $124.8\,\mathrm{MHz}$ during data transmission. This variation of PRF is no disadvantage for the WUR receiver; indeed, due to the higher pulse and energy concentration, the rectifier is kept active for a longer time. Adding to the modeling complexity, a UWB Packet has a limited length, determined by the size of its components, the preamble and the signal payload. For this OOK modulation, the preamble synchronization length has been selected to be 1024 symbols, while the length of the data is tuned by varying the size of the payload. More coarse-grained tuning of the signal can be obtained by modifying the coding of the symbol and therefore changing the symbol duration. This parameter is preferable to be as short as possible to allow for a precise OOK modulation. By careful choice of these values, the final length of the packet can be selected to be a divisor of the highest OOK modulation frequency, $10\,\mathrm{kHz}$, and then repeated to obtain on and off periods. As only the signal's energy is of concern, the payloads that make up the OOK signal can be generated randomly, be fixed, or even contain data destined to an already-on receiver, which makes the passive Wake-Up receiver unobtrusive.

The selected carrier wave is on Channel 2 at $3.9936\,\mathrm{GHz}$, as this channel is distant from ISM bands and therefore presents less interference due to unrelated communication protocols.

An increase of transmission strength can be obtained by setting the manual power control mode which is enabled by the *DIS_STXP* bit (bit-18) in the system configuration register located at address 0x04. In this mode, the user must program the desired transmit power setting for each frame. As frames become progressively shorter, greater amounts of boost may be applied to the preamble and data portions of the frame. Two different power setting are required for the header and for the preamble and data portions of the frame, both handled by register 0x1E, listed in the DW1000 register map. The maximum DW1000 output power is $-4\,\mathrm{dBm}$, a

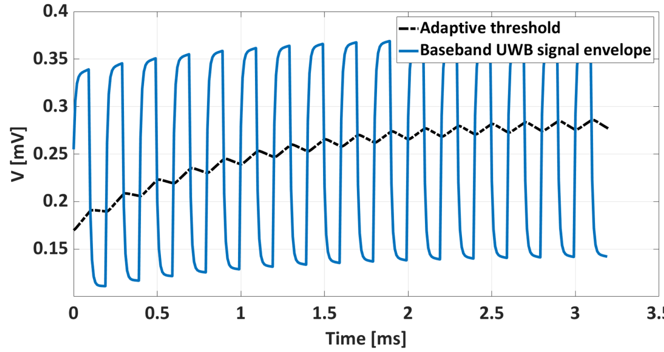

Fig. 6. Envelope detector and automatic average threshold output at the WUR sensitivity, $-48\,\mathrm{dBm}$ at at $3.9936\,\mathrm{GHz}$.

value measured at the antenna using the maximum power boost configuration. This setting does not respect the limitation imposed by Eq. 1, but provides deployment flexibility in case of specific edge applications or with low gain antennas.

VII. Experimental Results and Discussions

The results presented in this section demonstrate the effective improvement in terms of latency and power consumption between the DW1000 duty cycle approach and the proposed WUR framework. The following results consider the relationship between the frame duration and the output power in addition to the WUR sensitivity. We used as the reference antenna the WB002[4] from Decawave, which is designed for a wide-band reception and is normally used for precise distance measurement. Fig. 6 shows the WUR receiver behavior at the operating limit, $-48\,\mathrm{dBm}$. The blue line represents the output of the envelope detector consisting of the BAT15-04W and a $10\,\mathrm{pF}$ capacitor, while the black dotted line represents the adaptive threshold filter connected to the negative input of the LT1017 comparator. In this condition, the peak-to-peak difference between the reference voltage and the digital base-band signal is comparable with the LT1017 input offset voltage, the main constraint for the sensitivity of the receiver . Note that results in Fig. 6 are considered within a limited temperature range around $25\,^{\circ}\mathrm{C}$; For a wider range of temperature operation, it is recommended to verify temperature dependencies from the comparator datasheet. The measured power sequence of a low power device (see Fig. 1) equipped with our WUR radio is presented in Fig. 7. The system is generally in sleep mode (Time 0.02-0.04) and only the LT1017 comparator is active; in this state, the power consumption is $100\,\mathrm{\mu W}$, which reaches $180\,\mathrm{\mu W}$ during the address decoding (Fig. 7 - *WUR decoding*). If a correct pattern is received, the WUR triggers the main MCU. In this specific test, it is a Cortex-M4 from the STM32L4 series[5]. Afterward, it enables and configures the DW1000, which starts the ranging protocol characterized by an average power of $0.4\,\mathrm{W}$. Differences between the duty cycles approach and the solution proposed

[4] www.decawave.com/uwb-antennae-design-files
[5] www.st.com/en/microcontrollers-microprocessors/stm32l4-series.html

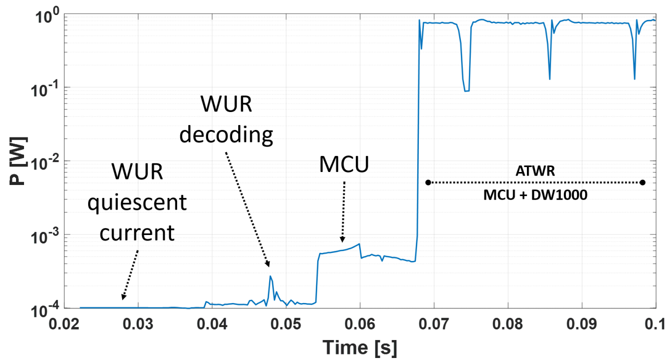

Fig. 7. Power consumption sequence of our WUR combined with a DW1000 transceiver.

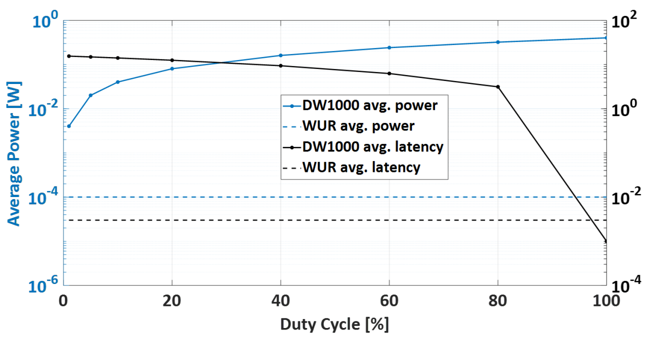

Fig. 8. Power consumption and latency comparison between the duty cycled low power listening and the WUR.

in this paper are highlighted in Fig. 8, where latency and power are compared. Considering a reception window of $156.7\,\mathrm{ms}$, the overall listening period at $1\,\%$ DC is above $15\,\mathrm{s}$, affecting the average latency ($7.5\,\mathrm{s}$). This is opposed to what can be observed at active percentages close to $100\,\%$; the power consumption is almost one-third of a Watt, with a consequent detrimental effect for battery supplied devices. On the other hand, our framework guarantees a latency in the order of tens of milliseconds, with energy supply requirements between 2 and 4 orders of magnitude lower. Due to the high frequency involved in the RF transmission, significantly more than standard $433\,\mathrm{MHz}$ and $868\,\mathrm{MHz}$ WUR implementations, in addition to the reduced budget link, the communication range is below $1\,\mathrm{m}$. However, optimized design implementation of the envelope detector is out of the scope of this paper, which demonstrates the possibility of using a single UWB commercial transceiver to enable a sub-mW asynchronous wake-up radio for ultra-low-power electronic devices.

VIII. Conclusions

This paper proposes a novel UWB asynchronous wake-up radio using only off-the-shelf components that can be combined with any existing UWB transceiver. To achieve this goal, we also proposed a wake-up signal protocol that generates OOK messaged using commercial UWB radios. The proposed wake-up radio schema also includes addressing to improve energy efficiency and power management. We evaluated it in our lab with experimental measurements. We demonstrate a drastic reduction of latency and power consumption with respect to standard implementations. Our $100\,\mu\mathrm{W}$ always-on radio requires $40\,\times$ less energy compared to low power listening at $1\,\%$ DC and $400\,\times$ at $10\,\%$ DC. Moreover, in these configurations, the DW1000 provides an average latency between $7.5\,\mathrm{s}$ and $750\,\mathrm{ms}$. Finally, we have shown the capability of a commercial UWB transceiver to generate an On-Off-Keying virtual modulation by constructing a predefined UWB packet sequence with specific timings and payload lengths.

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