Ultra Low Power Wake-Up Radios: A Hardware and Networking Survey

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***Abstract*—In wireless environments, transmission and reception costs dominate system power consumption, motivating research effort on new technologies capable of reducing the footprint of the radio, paving the way for the Internet of Things. The most important challenge is to reduce power consumption when receivers are idle, the so called idle-listening cost. One approach proposes switching *off* the main receiver, then introduces new wake-up circuitry capable of detecting an incoming transmission, optionally discriminating the packet destination using addressing, then switching *on* the main radio only when required. This wake-up receiver technology represents the ultimate frontier in low power radio communication. In this paper, we present a comprehensive literature review of the research progress in wake-up radio (WuR) hardware and relevant networking software. First, we present an overview of the WuR system architecture, including challenges to hardware design and a comparison of solutions presented throughout the last decade. Next, we present various medium access control and routing protocols as well as diverse ways to exploit WuRs, both as an extension of pre-existing systems and as a new concept to manage low-power networking.**

***Index Terms*—Wake-up radio, MAC protocols, energy efficiency, multichannel, asynchronous communication, Internet of Things, survey, green networking.**

I. INTRODUCTION

THE INTERNET of Things (IoT) offers a new Internet frontier considering networks between smart physical objects or "Things", which are embedded with sensors, actuators, and/or processing capabilities [1]. IoT provides novel applications for various fields such as Smart Cities, building automation, domotics, logistics, Smart Grid, e-Health, and agriculture [2].

A founding pillar of the IoT concept is the availability of low-cost devices with low-power wireless communication capabilities, often deployed as part of a larger Wireless Sensor Network (WSN) [3], to provide both sensing and actuation capabilities. These devices are usually powered by batteries with restricted size and capacity [4], and thus have limited lifetime requiring careful power management. With the increase in the number of IoT devices, replacing or recharging batteries frequently will not only be costly but infeasible as well. Therefore, prolonging the lifetime of these devices, or even better achieving perpetual operation, becomes fundamental for the realization of the IoT vision.

Traditionally, these problems have been addressed by the introduction of low-power radios and of *duty-cycling* Medium Access Control (MAC) protocols [5]. Notwithstanding, one of the most power hungry tasks performed by these nodes is low-power wireless communication. In most applications, its consumption far exceeds that of sensing, actuation, and processing, and became the main bottleneck in extending device lifetime.

Recent developments in CMOS power consumption have led to the birth of a new design paradigm of *wake-up radios* (WuRs) to further reduce power consumption and, in combination with energy harvesting [6], [7], reach the goal of the perpetual operation.

A. From Duty-Cycling MACs to Wake-Up Radios

The main reason duty-cycling MACs alone can not sufficiently extend the lifetime of a node is that the consumption of low-power wireless radios is almost the same when listening for transmissions as while transmitting. For example, the widely used CC2420 radio module consumes 21.8 mA in listening mode and 19.5 mA in data transmission mode [8]. If such a radio would be always-on (listening for other transmissions or transmitting) it would deplete reasonable sized batteries in less than a week.

During duty-cycling, the nodes are periodically put into sleep mode and are woken up only to transmit or to receive. Unfortunately, the so called duty-cycling ratio (the ratio of time the radio is in transmit or receive mode to time off) cannot go arbitrarily low, due to:

(i) *idle listening:* occurs when the node monitors the communication medium for ongoing transmissions, but there is no data to be received by the node. Since nodes must listen periodically to limit data latency, there is a listening power consumption that cannot be avoided, even in low data traffic scenarios.

(ii) *overhearing:* occurs when a node receives packets from its neighbors that are not intended for that node, leading to energy waste, especially when the network density is high and the data traffic is heavy.

Manuscript received August 11, 2016; revised December 29, 2016 and April 26, 2017; accepted June 15, 2017. *(Corresponding author: Amy L. Murphy.)*

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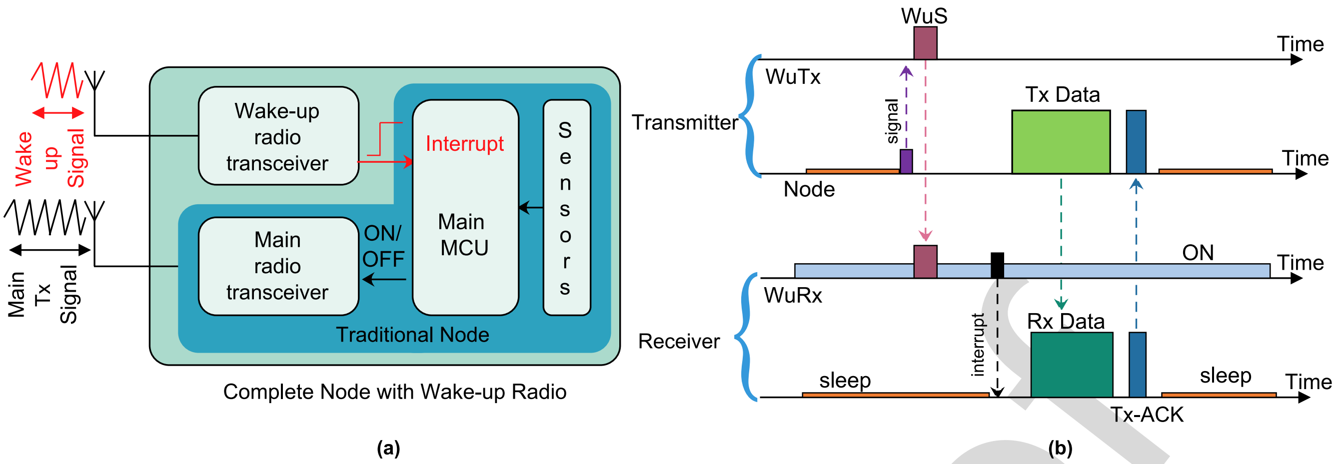
Digital Object Identifier 10.1109/COMST.2017.2728092



AQ1 Fig. 1. (a) Overall Wake-up Radio architecture. The blue region indicates the traditional node integrated with the Wake-up Radio. (b) Remote triggering using wake-up radio scheme.

Due to the sleep intervals, duty-cycling protocols also introduce significant *data latency* since no information can be sent or received until the nodes wake-up.

Finally, duty-cycling MAC protocols must either maintain time synchrony to make sure transmitters send when receivers are awake, which induces a time synchronization overhead, or in the case of asynchronous operation the MAC protocol must employ continuous (or multiple) transmissions to ensure reception. The longer the sleep interval of the receiver, the longer the continuous transmission must be, dictating a lower-bound on achievable duty-cycles.

These design compromises have led the sensor network community to design and implement various MAC protocols resulting in a "MAC Alphabet Soup" for sensor networks [9] each targeting different scenarios and offering different compromises throughout the design space of energy consumption, latency, throughput, and fairness. Nevertheless, duty cycling protocols may not be suitable for delay sensitive and event-driven applications, and prolonging device lifetime requires extreme compromises in other dimensions of the design space, limiting the applicability of the technique.

The introduction of *wake-up radios* aims to provide a novel hardware solution with listening power consumption orders of magnitude lower than that of low-power radios, promising results towards eliminating the aforementioned problems of idle listening, overhearing, continuous transmissions, and data latency.

In a WuR architecture, as shown in Fig. 1 (a), an *ultra-low power*, secondary radio module with a receiver *consuming a few micro watts of power* is along side the primary, low-power radio. Since its power consumption is several orders of magnitude lower than that of a traditional low-power radio, the WuR can be kept always-on, leading to a use in contrast to the duty cycling operation descried earlier for the main radio. One modality in which the WuR can be used is illustrated in Fig. 1 (b). In this setting, the main radio is kept in a deep sleep, or off mode, until it is needed. Instead when a node has a data packet to send, it sends a special packet known as a *wake-up signal (WuS)* using its *wake-up transmitter (WuTx)*. The always-on *wake-up receiver (WuRx)* detects this WuS, and generates an interrupt to the main node's micro-controller to switch it from sleep to an active mode. Subsequently, the main micro-controller turns on the main radio transceiver to exchange data packets with the other node in a conventional manner.

This seemingly simple and obvious mode of operation has been made possible by recent advances in CMOS power consumption, allowing both the implementation of the ultra low power analog front-end to receive the WuS as well as a low power digital component used inside the WuR for address decoding.

B. Wake-Up Radio: Benefits and Design Trade-Offs

As mentioned previously, idle listening is a significant contributor to the overall energy consumption of duty cycling nodes. With the introduction of a WuRx with orders of magnitude lower consumption, the WuR approach minimizes this unnecessary energy wastage, as the main radio and the node will be activated only when there is an actual transmission.

In addition, some WuRs add circuitry for an addressing mechanism that can be used to solve the issue of overhearing by decoding an address embedded in the packet, waking up only a specific node rather than the entire neighborhood.

Further, since the WuRx can be always-on, the node can operate in a purely asynchronous manner, activating the main radio on-demand, without requiring continuous transmissions.

Finally, since the time taken to trigger the main node is on the order of milliseconds (ms), the latency problem faced by duty-cycling MAC protocols is also reduced.

While the concept the WuR seem simple and the benefits look promising, the hardware implementation and its usage as part of the larger system present several challenges and design trade-offs.

At the hardware design level, achieving listening with very low power consumption places limits on RX processing and on the components that can be used in the WuRx. Various hardware options had been explored in literature exploring a wide range of options, including some that are not radio frequency (RF) based, e.g., optical or acoustic.

Strict bounds on power consumption also limit the choice of modulation schemes and receiver complexity, which, as a consequence, limit receiver sensitivity, and ultimately the achievable communication range. As the main radio is triggered by the WuR, this range limitation of the WuR inherently limits the communication, regardless of the main radio's capabilities. As we will show throughout our survey, various compromises have been taken in this regard, from focusing on short-range scenarios (Body Area Networks), to using out-of-band sub-GHz WuS, to using greatly increased WuTx power.

As far as the MAC protocol is concerned, pure asynchronous operation enabled by the always-on WuRx largely simplifies protocol design. However, the development of new WuR specific MAC protocols are required, taking into account the dual radio setup of the WuR architecture.

C. Contribution and Related Work

This paper offers:

(i) An extensive survey and classification of the state of the art in wake-up receiver prototypes implemented and tested since 2002, specifically 75 RF based wake-up radios (Table VIII) and 10 non-RF based prototypes (Table IX).

(ii) An extensive survey and classification of the state of the art in MAC and routing protocols designed to take advantage of wake-up radio technology.

(iii) The identification and discussion of emerging applications that can benefit from WuR technology.

(iv) An outline of open issues, challenges, and future research directions for WuR based systems.

Other hardware surveys exist [10], [11], identifying key characteristics of the wake-up technology such as power consumption, sensitivity and data rates, but focusing only on characteristics at the hardware layer. While we also present the hardware, we offer insight into its impact on the networking stack software.

Alternate work considers the validity of the combination of wake-up radios and energy harvesting [12]–[14].

Similarly, several studies have emphasized the benefits of wake-up radios for extending node lifetime [11], [15], [16], while also improving reliability and reducing latency [17], [18]. Our work compliments and extends these by reporting on several wake-up radios that directly harvest energy from the wake-up signal, referred to as passive in Table VIII, as well as on the consumption values of the receivers, a critical element for considering them as a component in a system with energy-harvesting.

On the software side, the last decade has seen a plethora of low-power communication protocols [19], especially focused on the MAC layer [5], [20]–[22] or on general energy conservation schemes [23]. A brief survey of wake-up receivers for WSNs offered an introduction to the technology [24], focusing on software only at the MAC layer. Routing has been studied in general for WSNs in isolation [25]–[28], or in cross-layer solutions [29], [30]. Nevertheless these surveys do not focus on the unique properties of the wake-up radio technology, and the impact it has on this layer.

TABLE I
ACRONYMS FOR WAKE-UP RADIO TECHNOLOGY

WuR	wake-up radio, the secondary low-power module
WuRx	wake-up receiver
WuTx	wake-up transmitter
WuS	wake up signal, the message sent by the WuTx

D. Structure of This Article

The remainder of this paper is organized as follows: Section II depicts the main characteristics of a wake-up radio. Section III discusses the design space and architecture of wake-up radios followed by some of the main implementation requirements when designing wake-up radio based systems. Sections IV and V discuss the state-of-the-art wake-up radio hardware designs and comparative analysis between each characteristic, respectively. The integration of different medium access control and routing protocols that are based on wake-up radios are presented in Sections VI and VII. In Section VIII we briefly discuss some of the application scenarios that can benefit from wake-up radios. Finally, in Section X we conclude this survey with open research issues.

II. WAKE-UP RADIO DEFINING CHARACTERISTICS AND REQUIREMENTS

Before we begin, we summarize in Table I the key terminology we use throughout our survey to identify components of the wake-up technology.

The technology and design considerations for the WuR play a key role in determining the efficiency of low power sensor networks. For the WuR to operate effectively as part of the larger system in a multi-user environment, it should consider the following design points:

(i) *Power consumption:* The most important feature of the WuR is its low power consumption in active mode. In fact, as its use requires the addition of new hardware on top of the main node, the device itself must consume no more than tens of micro-watts. Specifically WuR's active power should be below that of the main radio's sleep power [31] to provide a positive balance between power saved and used. This is the main specification driving WuR design.

(ii) *Time to wake-up:* The node attached to the WuR must wake-up with minimum latency upon reception of WuS to avoid latency incurred from multi-hops toward the sink and to increase the overall responsiveness of a purely asynchronous network. A range of protocols and applications can benefit from WuR based systems provided that the latency is low. For example, applications in health-care have strict latency requirements and cannot support introducing long delays due to the wake up procedure.

(iii) *False wake-ups and interference:* If all nodes in a sensor network rely on the same wake-up strategy, when the WuTx tries to wake-up a node, it will trigger all the nodes in the neighborhood causing significant energy waste. This causes unnecessary activation of many nodes that should be avoided. There are two possible sources of false wake-ups: 1) nodes waking up when receiving a WuS intended for another node, and 2) interference from nearby devices operating at the same frequency. To tackle the first, the WuR can employ a node addressing and decoding capability to trigger only the intended node. This allows the WuRx to avoid generating an interrupt if the WuS was not intended for it, however it introduces complexity and often consumption at the WuRx. Second, interference and background noise that can result in erroneous wake-ups must be filtered. A WuRx must have enough local processing capability to differentiate a WuS from ambient interference, without using the main node's processor. Due to the low power budget, only basic modulation techniques can be used requiring a simple receiver structure [32]. Modulation schemes such as on-off keying (OOK), pulse width modulation (PWM) or amplitude shift keying (ASK) can be used to reduce the possibility of devices interfering with each other. A preamble can be used to differentiate noise from a valid WuS, thus avoiding false wake-ups. In addition, the WuS must not be missed by the targeted node, as retransmissions are costly in terms of power consumption and latency. To ensure this, a feedback loop such as WuS acknowledgment (WuS-ACK) can be employed by the WuRxs indicating the successful reception of the WuS.

(iv) *Sensitivity and range:* In WuR design, receiver sensitivity is an important parameter as it provides the lowest power level at which the receiver can detect a WuS. Generally, high sensitivity requires more power hungry electronics at the receiver side, thus high power demand. In contrast, low sensitivity for the same communication range will require high radiated power at the transmitter side. Because of this, sensitivity requirements often leads to over-design to ensure reliable communication in adverse conditions. When the WuR is used to trigger a higher power radio, ideally it should have the same range. Unfortunately this is not reasonable with the power constraints, therefore, most WuR designs target tens of meters of communication range to support many application scenarios [33]. Very short communication ranges make WuR impractical as high node densities would be required to cover a short distance in a multi-hop fashion increasing node and energy costs. Another side effect of a short communication range is the increase in the hop count messages must traverse to reach the sink, increasing the overall data latency. The wake-up range that can be achieved with most current WuR designs is typically around 30m a value that can be improved by using techniques such as antenna diversity [34] and directional antennas [35].

(v) *Data rate:* The overall power expenditure of a node is not only a function of physical layer properties such as carrier frequency, radio architecture, and the choice of the antenna, but is also a function of the amount of time the radio spends to deliver the data packet over the air. This time depends on the data rate supported by the WuTx and the protocol overhead to establish and maintain the communication link. Data rate is, therefore, one of the key factors defining the power consumption of WuRs. For example, a WuR with 100 kbps will consume almost half the power of a 50 kbps WuR for the same payload size. For a WuTx with low data rate, the bit duration and the power required to send the WuS will be significantly higher. Due to the longer bit duration, the modulation will keep the transmitter active for a longer time. On the WuRx side, the time and the energy required to generate the wake-up interrupt will also be significantly higher as the receiver and the demodulation circuitry will be active until the transmission ends. A higher data rate can be seen as a way to improve energy efficiency and to achieve faster wake-up. While a high data rate reduces wake-up latency, a longer bit duration increases the communication range and the reliability of the WuS. At a lower data rate the energy per bit exhibited by the transmitter is higher, which can be accumulated by the WuRx while receiving the WuS. A high data rate is not strictly required by the WuR, especially if it is only used as a triggering device as only a few bytes of data are required.

(vi) *Cost and size:* To integrate the WuR into existing sensor nodes, it should be cost effective. To make the WuR feasible [24], the cost of this additional hardware should be in the range of 5-10% of the cost of the complete sensor node. This is, nevertheless, a loos requirement, as some applications can support higher costs if gains are sufficient. Further, standard off-the-shelf components can be used to speed the development and to reduce the overall cost as compared to designing a single chip solution.

(vii) *Frequency regulation:* Finally, WuR designs should adhere to frequency regulations in industrial, scientific and medical (ISM) bands. It must also comply with communication standards such as the maximum allowed effective radiated power (ERP) used to transmit WuS.

III. ARCHITECTURE AND TAXONOMY OF WURS

We begin this section by presenting a generic architecture for WuRs and the building blocks that makeup the complete hardware solution. We discuss the functionality of different hardware components and how these devices can be powered and interfaced with traditional sensor nodes. We then move on to present a taxonomy of WuRs, illustrated in Fig. 4, showing multiple dimensions that distinguish the designs from one another.

A. Generic Architecture of WuRs

While WuRs can be constructed in many different ways, each exposing different performance and peculiarities, there are some common building blocks utilized by all designs. Two distinguished implementation approaches have been identified,

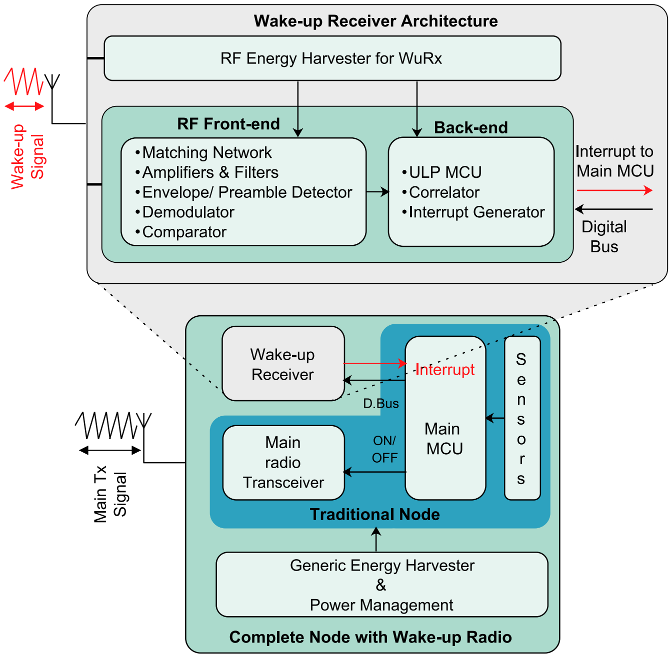


Fig. 2. Expanded view of the generic wake-up receiver architecture with energy harvesting capabilities.

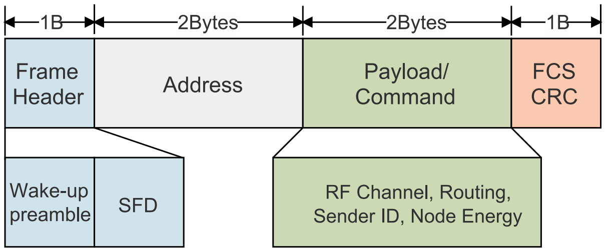


Fig. 3. Typical wake-up signal packet structure.

i.e., prototypes constructed using off-the-shelf discrete components and implementations that exploit CMOS technology for constructing integrated circuits. Power consumption is one of the driving factors behind the use of WuRs due to the energy saving that it can provide. Typically, CMOS implementations achieve improved performance because they better integrate all the components directly on silicon, i.e., more dense integrated circuits result in smaller IC footprints for the same function, hence consuming less power. On the other hand, when using discrete components there are more constraints on each single component selected to build the circuit resulting in worse average performance than CMOS-based designs.

Fig. 2 illustrates the current architecture and the different functional blocks that form a complete WuRx. This architecture is divided into two sections: the *RF front-end* and the *back-end*.

The WuS is first received by the RF front-end via the antenna and then passes through the matching network that filters and boosts the incoming WuS. After input matching, an envelope detector performs signal detection and conversion to baseband signal making the circuit simpler and energy efficient. Then, the signal passes through the amplifiers, often the low noise amplifier (LNA) for increasing the sensitivity of the receiver by amplifying weak signals while meeting noise requirements. The LNA dominates in terms of power consumption. Therefore, while designing ultra-low-power WuRxs it is essential to eliminate some, if not all, of these power-hungry RF components, to reduce power consumption. The voltage multiplier rectifies the RF energy and converts this input signal into a direct current (DC) signal. Usually, the voltage multiplier is constructed by cascading capacitors and zero-bias Schottky diodes. The more energy in the RF signal, the greater the voltage change at the output of the rectifier, which is sensed using a comparator. When there is enough energy to trigger the comparator, the back-end is able to issue an interrupt to the main micro-controller. This back-end can also consist of an ultra-low power micro-controller or correlator circuit that decodes and filters the node address and generates an interrupt.

From the energy point-of-view, one of the hurdles is to supply sufficient energy to operate these devices in a self-sufficient manner without replacing batteries frequently. One of the approaches to achieve this is through Wireless Energy Harvesting (WEH). As illustrated in Fig. 2 the subsystem can include one or more energy harvesters that convert the ambient energy into electrical energy. The *Generic Energy Harvester* module that can power the complete node (including the WuRx, the main transceiver, the main MCU and the sensors) exploiting different energy sources such as magnetic, solar, wind, and mechanical vibrations. Also a separate and standalone *RF Energy Harvester*, dedicated only for the WuRx, can be employed making the subsystem fully passive, i.e., the energy can be scavenged from the incoming WuS itself. The RF-EH unit consists of an antenna and a power management unit (PMU). The PMU basically controls the power supplied to other blocks of the WuRx. In some applications it is possible to directly power the WuRx using the harvested energy from the WuS without energy storage, however, this may not be a viable solution. An alternative would be to include a storage component such as rechargeable batteries or super-capacitors acting as an energy buffer for the subsystem. The main purpose of this storage component will be to accumulate and preserve the harvested energy for later use, thus supporting variations in the RF power level emitted by the WuTx. The wake-up range is relatively short due to free space path loss, low sensitivity, and efficiency of power harvesting at the WuRx. As a result, the WuS is usually transmitted at high power.

The wake-up transmitter, which is usually not detailed in the literature, also plays an important role from the system point of view. Most of the works mentioned in this survey use the standard node's transmitter as a WuTx such as CC2420 or CC1101 [11], [15], [36]–[40].

Finally, we briefly address the content of the WuS, whose packet structure must meet compliance requirements and standards to be used by different technologies. Recent attempts [41] have been made to standardize this for WuRs in medical applications.

A typical WuS packet is illustrated in Fig. 3:

(i) *Frame Header:* The frame header consists of the wake-up preamble and start frame delimiter (SFD), a standard byte pattern agreed between the transmitter and the receiver. The preamble contains a set of bits that allow the transmitter and receiver to synchronize their bit intervals and the SFD indicates to the receiver the actual start of the frame and when to start decoding the contents of the packet. The size of the SFD is typically fixed at 1B.

(ii) *Address:* The optional address field contains the destination node ID for identifying the intended receiver. While most designs in our literature survey use node IDs up to 2 bytes [38], [42], the size of this field can be varied depending on the capabilities of the WuRx as discussed below. One of the dimensions of our taxonomy, described next, considers the benefits and costs of addressing inside the packet.

(iii) *Payload / Command:* This field contains the actual application data, command or extra instructions specified by the user or application.

(iv) *Error detection:* Finally, to check data integrity, a frame check sequence (FCS) using a cyclic redundancy code (CRC) is applied. While simple, the CRC provides a high degree of error detection at high speed.

B. Taxonomy Overview

For the purposes of this survey, we identify four major dimensions for classifying a WuR: power source, addressing capability, channel usage and communication medium. Fig. 4 shows multiple options for each of these dimensions and maps, when possible, the WuRs from Tables VIII and IX. We address each major dimension, beginning with power, as it has the most significant impact on system efficiency.

(i) *Power (Passive):* While the WuR requires power to receive a signal, it does not require continuous power. Instead, it can harvest energy, e.g., from the ambient environment or from the incoming wake-up signal itself (Fig. 2). The latter case places a burden on the transmitter side as the WuTx must modulate and transmit the WuS long enough, typically a few seconds, for the WuRx to detect the signal and accumulate enough energy to power the trigger circuitry. The longer the WuTx is active, the more power is consumed. Moreover, this process requires additional hardware at the WuRx side, thus increasing circuit complexity. The process of accumulating energy also delays the wake-up of the main node, affecting network performance by increasing latency and reducing data throughput. Although passive WuRs are energy efficient and offer extended lifetimes, they often have a shorter operating range than active WuRs, typically only a few meters.

(ii) *Power (Active):* To address the constraints of passive WuR, the majority of research efforts focus on fully-active WuRs that receive a continuous, external power supply either using batteries or a renewable energy harvester hosted on the main node. The objective of this design is to increase sensitivity, providing longer operational ranges with very low power consumption. 65% of the prototypes that we present in this survey are active WuRs.

(iii) *Power (Semi-active):* In semi-active WuRs, a minority of the components of the receiver, e.g., correlator, comparator and decoder, require continuous power from an external source while the RF front-end remains passive.

Next we consider the recipient of the WuS, specifically whether it can be broadcast-only, with the intent to reach all nodes in range, or can contain an address as shown in Fig. 3, intended for a node with a specific ID.

(i) *Addressing (ID-Based):* Optionally, the WuS can contain a bit sequence, typically 8 to 16 bits, for selective node addressing. This increases the size of the packet, but reduces false wake-up and thus overall system energy consumption. After reception of the WuS, the WuRx checks if the signal is intended for it. If so, it triggers and wakes up the main node for data reception. This scheme is referred to as ID-based wake-up and is mostly used to construct unicast-based systems. It should be noted that energy is consumed to decode a wake-up packet and this is typically performed by an external, low-power microcontroller. Further, the length of the address encoding affects performance. While a long address code is more robust against false wake-ups, it requires a long transmit time, hence more power is consumed. Studies [43] consider the trade-off between the length of the wake-up signal and the energy savings, revealing that the energy used to send the selective wake-up signal only pays off if many nodes are not falsely woken up. In other words, the energy required to transmit the wake-up signal is higher than the energy lost during false-wake up. For low density networks where little data is exchanged, the extra cost of ID-based addressing may not be worthwhile.

(ii) *Addressing (Broadcast):* When the entire neighborhood of nodes receives the wake-up signal, the scheme is referred to as broadcast based wake-up. Broadcast based wake-up can reduce the data latency w.r.t. ID-based systems since the receiving node need not decode a wake-up packet to analyze the recipient ID, but can instead immediately trigger its main radio transceiver after receiving the preamble. However, this is potentially expensive in terms of total system power consumption as all neighboring nodes are woken up.

Next, we turn to how the WuR transceiver utilizes the channel for WuS transmission. Note that the choice of channel or frequency depends on the application and the device to which the WuR is attached.

(i) *Channel (In-Band):* In in-band communication, the main node's transceiver and the WuR use the same frequency band, i.e., either 2.4GHz or sub-GHz and can share the same antenna. This technique is cheaper as there is no need for a separate antenna.

(ii) *Channel (Out-of-Band):* In out-of-band systems, the main node and the WuRx are equipped with separate transceivers, each operating at different frequencies. For instance, the WuR prototype presented in [38] operates at 868 MHz while the main data radio operates at 2.4 GHz band. Using frequency or code

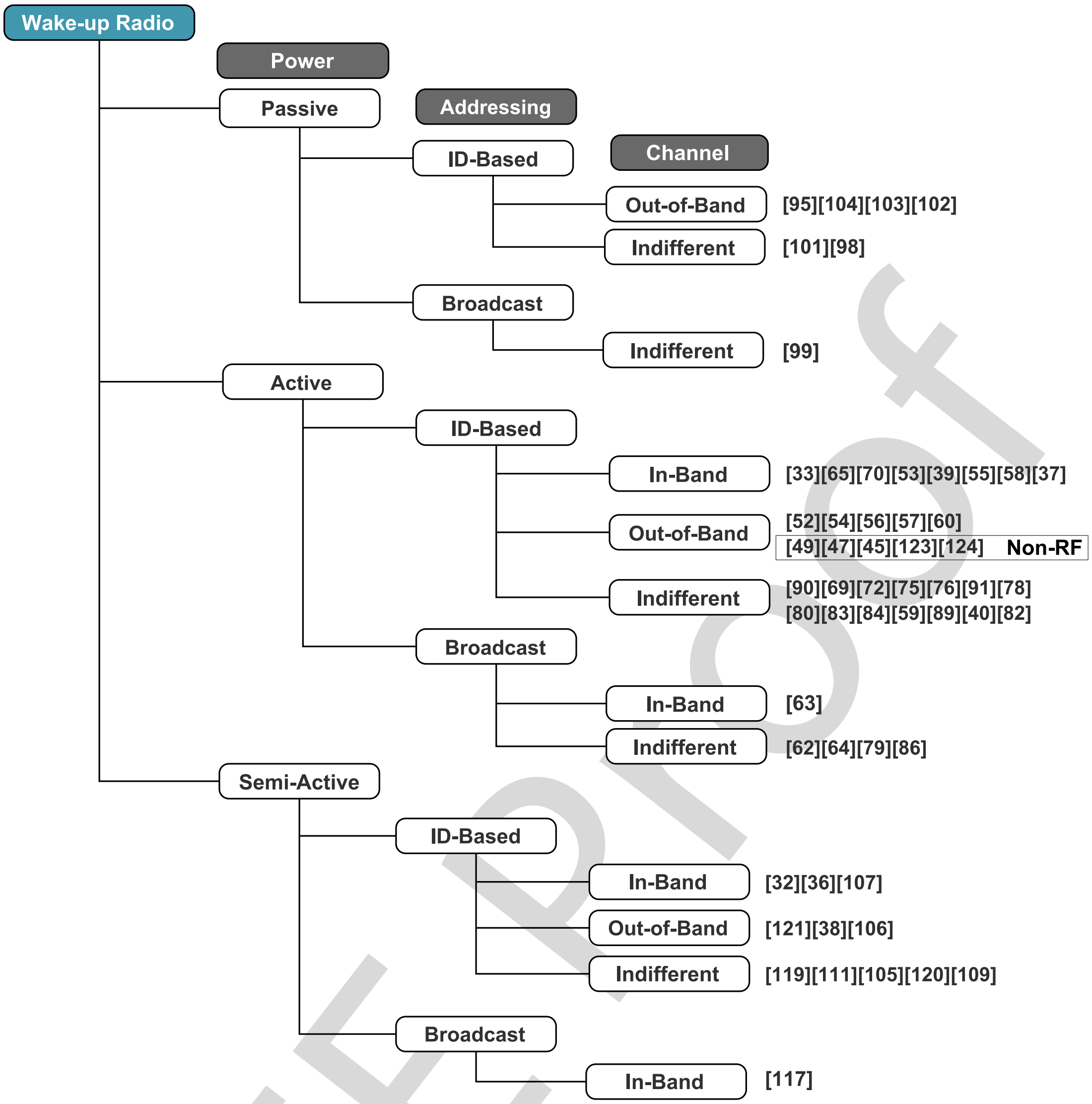


Fig. 4. Taxonomy of wake-up radios showing the hardware design space.

division techniques such as frequency-hopping spread spectrum, this separate channel can further consist of multiple channels to be able to wake-up specific nodes. The benefits of using separate channels for WuS transmission and data include decreased interference from neighboring nodes operating in the same frequency band and increased signal capacity. However, equipping the WuR with separate channel capability may increase the cost and complexity of the system design.

Finally, we look at the different communication mediums that can be utilized for WuS transmission. Fig. 4 does not explicitly show this as a vast majority of the systems we survey fall into a single category, namely RF-Based. Instead, we explicitly indicate the few systems that are not RF-based, and refer the reader to Table IX for details.

(i) *Medium (RF-Based):* If radio signals such as extremely low frequency (~3 kHz) to extremely high frequency (up to several GHz) are used for signaling, the scheme is referred to as *RF based* wake-up. RF based WuRs have been very widely used and will be discussed in more detail in the next section.

(ii) *Medium (Acoustic):* Acoustic based wake-up such as ultrasonic and audio signals have also been considered. This medium does not require any special infrastructure and the audio signals can be easily generated by speakers or smart phones. Yadav *et al.* [44], Lattanzi *et al.* [45], Hoflinger *et al.* [46], and Sánchez *et al.* [47] have proposed WuR designs based on sound wave for WuS transmission.

(iii) *Medium (Optical):* Optical as a communication medium for WuRs has also be utilized for indoor sensor networks [48], [49]. For example, Mathews *et al.* [48] have used Free Space Optics (FSO) for sending WuS.

As a system designer, this taxonomy serves as a guide to the available WuR technologies that could meet the constraints of the system. Knowing if continuous power can be provided in a given environment can direct one along the branch with the appropriate power source. Knowing the approximate node density and the expected data rate can serve as indicators for

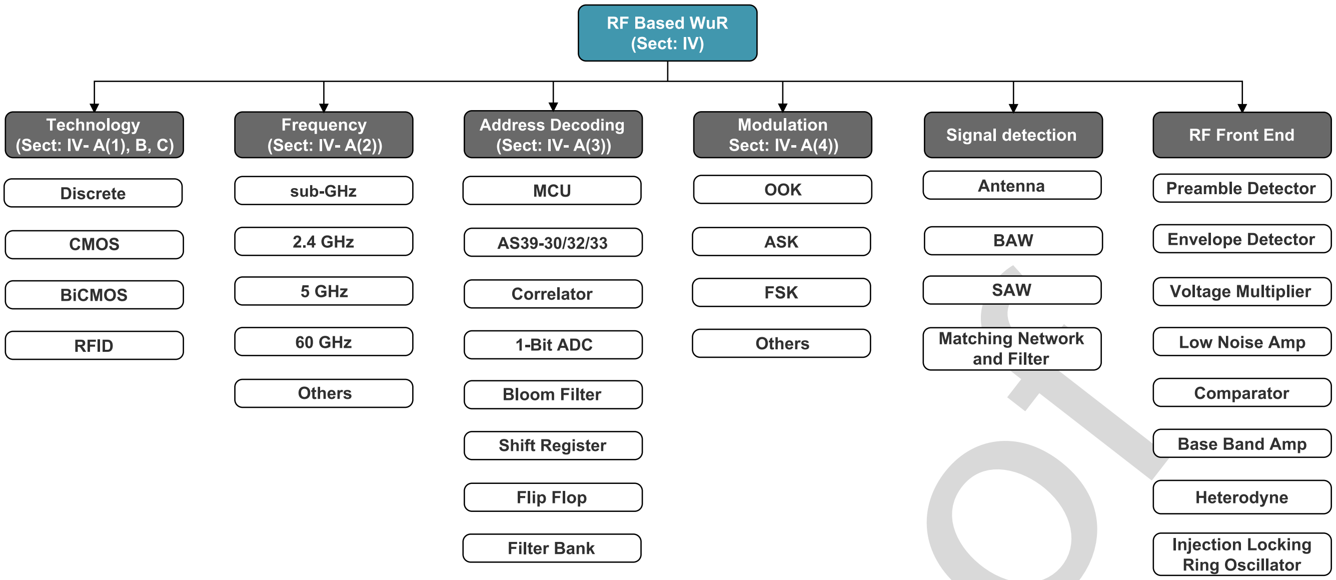


Fig. 5. Defining characteristics of RF-based WuRs with various building blocks. Wake-up radios meeting each characteristic appear in Tables II to VII while Tables VIII and IX provide the full summary of each surveyed prototype.

whether unicast, ID-based addressing or broadcast communication is most appropriate. Finally, the amount of expected data to be transferred can lead one to a solution where the WuS is on a same or different channel.

IV. State-of-the-Art Wake-Up Radios

Following this taxonomy for system designers, we now shift focus to the hardware composition of the various prototypes described in the literature. This section offers a comparison of 75 RF-based WuR prototypes, summarized in Table VIII. To offer a clear picture of the current research landscape, we organize this section first along the power source dimension outlined in the previous section: active, passive, and semi-active systems.

Inside our description of active radios, we offer a categorization, overviewed in Fig. 5, that defines the key hardware characteristics. We focus on four: core fabrication technology, frequency usage, address decoding, and modulation techniques.

Following this in-depth discussion of active RF-based WuR, our more concise discussions of passive and semi-active focus on the technology only.

Within each subsection we offer a table categorizing the radios of Table VIII according to the options for each feature, highlighting (in bold and yellow) the prototypes that are described in detail in the text. Not all prototypes appear in each, separate table, as not all information is known about each prototype, preventing us from adding it to the tables.

We end the section with a brief summary of non-RF WuRs and a discussion.

A. Active Wake-Up Radios

In this section, we present active WuRs that require an external current source to receive a packet. In most cases, they are used in an always-on manner, but we defer this usage discussion to later. As previously mentioned, we divide our discussion of active WuRs into four categories: the technology used to realize the prototype, operating frequencies that have been utilized in different bands, address decoding techniques, and wake-up signal modulation.

TABLE II
WuR Categorization Based on Technology

Technology	**Reference No.**
Discrete	[33], [50], [51], [52], **[39]** , [53], [54], [55], [56], [57], [37], [40], [58],
CMOS	**[59]** , **[60]** , **[61]** , **[62]** , [63], [64], **[65]** , [66], [67], [68], [69], **[70]** , [71], [72], [73], [74], [75], [76], [77], [78], [79], [80], [81], [82], [83], [84], [85], [86], **[87]**
BiCMOS	[88], [89]
RFID	**[90]**

1) Technology: The overall power consumption of the WuR depends on its design technology as well as its implementation. Mainly, the chip fabrication technology such as CMOS and BiCMOS for digital circuits and the use of off-the-shelf discrete components for analog circuitry. Although off-the-shelf components allow quick implementation, CMOS based WuRs are more energy efficient and have smaller form factors.

Use of off-the-shelf discrete components and IC packages has allowed designers to simplify and foster rapid prototyping of WuRs with low power consumption, low cost, ease of changes, and reliability.

Petrioli *et al.* [39] presented a WuRx using fully discrete components that support four different channels in a 2.4 GHz band, thus enabling node addressing. The receiver front end consists of the antenna, low noise amplifier and three power slitters followed by the filter bank. According to the tests, the sensitivity of the WuRx is -83 dBm, while its power consumption is 1620 μW. The line-of-sight communication range

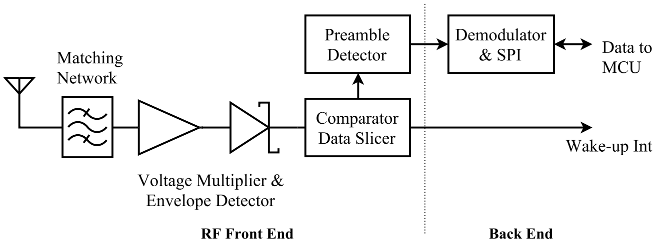


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Fig. 6. Discrete components based WuRx architecture [40].

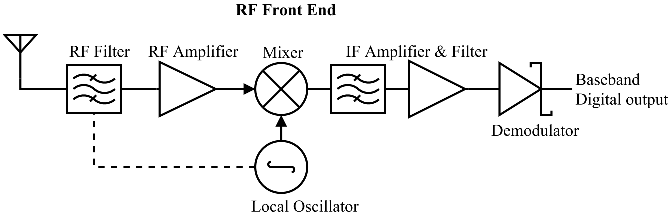


Fig. 7. Generic Block diagram of Heterodyne WuRx [62].

is 120 m, the highest range attained using low complexity receiver design. However, this design also has higher power demand compared to other WuRxs in this category and does not provide the details for the transmission power required to achieve this range.

In recent years power consumption of CMOS devices has greatly reduced allowing researchers to design ultra-low power circuits. There are 29 WuR prototypes based on CMOS technology.

In chronological order, the idea of developing and using ultra-low power radios as WuRs was first conceived by the PicoRadio project [59], which proposed a CMOS based node architecture that could be used both as a data radio and as a WuR using a carrier frequency of 1.9 GHz with data rate up to 100 kbps. The PicoRadio has a 10 m range and consumes around 380 μW from a supply voltage of 1 V. However, not much detail was provided on the hardware side.

Many of the proposed CMOS based prototypes have adopted a heterodyne approach. Heterodyne is a method to convert an incoming high frequency RF signal into one at a lower frequency by mixing two or more signals, where high gain and selectivity could be obtained with relative ease (Fig. 7).

Pletcher *et al.* [60] proposed a 1.9 GHz WuRx chip consuming 65 μW from a 0.5 V supply in an active mode (receiving and decoding the WuS). The receiver data rate and the sensitivity are 40 kbps and -50 dBm, respectively using OOK for WuS modulation. The design was further improved in [62] by using an "uncertain-IF" architecture to reduce the power consumption to 52 μW with enhanced data rate and sensitivity of 100 kbps and -72 dBm, respectively. The WuRx consists of BAW resonator for network impedance matching, a front-end-IF (Intermediate Frequency) amplifier for RF signal conditioning and amplification followed by an envelope detector for extracting the shape of the signal and converting it to direct current (DC) for triggering the node's MCU.

A simulation based super-regenerative heterodyne WuRx using duty cycling scheme is proposed by Yu *et al.* [61]. The super-regenerative WuRx consists of an isolation amplifier as an interface between the antenna and oscillator providing network matching followed by an envelope detector. To reduce power consumption, the oscillator is duty cycled at 10%. With duty cycling, the WuRx dissipates an average power of 56 μW in listening mode for 100 kbps OOK modulated signal using 2.4 GHz carrier frequency. However, this power consumption increases drastically to 525.6 μW at 1.8 V supply if no duty cycling is applied. Similarly, the WuRx prototype presented by Yoon *et al.* [70] also employs duty cycling. The proposed WuRx features two modes of operation; monitoring mode (MO) for receiving the preamble and identification mode (ID) for node address decoding. The WuRx is only duty cycled in the MO mode while in the ID mode the duty cycling is terminated and the data is received at higher data rate. In MO mode this node consumes as low as 8.4 μW from a 1.8 V power supply offering a data rate of 1 kbps. As a consequence of high bit rate of 200 kbps employed for address decoding, the power surges to 1100 μW for the receiver sensitivity of -73 dBm.

Another 2.4 GHz based heterodyne WuRx was proposed by Drago *et al.* [65]. The WuS is modulated using pulse-position-modulated (PPM) impulse radio modulation scheme. The main building blocks of this WuRx front end are an antenna, a matching network with an on-chip inductor, and a local-oscillator (LO) generator for down-converting the frequency. This IF signal is then amplified using multiple frequency IF-amplifier and then down-converted to baseband by a full-wave rectifier. To achieve low power consumption, the receiver front end as well as the LO generator are duty-cycled at pulse level, thereby reducing the power consumption to 415 μW. The full WuRx prototype achieves a sensitivity of -82 dBm at a data rate of 500 kb/s with energy efficiency of 830 pJ/bit.

There are also designs reported in the literature with power consumption above 1000 μW [64], [75], [87], [89] compared to the ones discussed earlier. The WuRx proposed by Bdiri and Faouzi [87] has attained the longest communication range of 82 m using heterodyne approach at transmission power of 10 dBm with receiver sensitivity of -60 dBm. However, at the same time this particular WuRx has the highest power demand of 5247.5 μW when receiving and decoding the WuS. Other heterodyne based WuRx prototypes achieving power consumption between 22 μW and 100 μW have also been reported in [77], [78], [81], and [84].

Radio-Frequency Identification (RFID) technologies have been used as WuR for accomplishing asynchronous multi-modal wake-up where an off-the-shelf RFID tag and an RFID reader has been utilized as a WuRx and WuTx, respectively. Fig. 10 illustrates a simple architecture for utilizing RFID technology for WuR systems.

An off-the-shelf active RFID tag based WuRx is simulated in [90]. RFIDImpulse uses an RFID reader as a WuTx to trigger an RFID tag that is attached to a remote sensor node at an operational distance of up to 30 m while consuming 80 μW of power. However, this receiver does not utilize addressing to selectively wake up a sensor node.

TABLE III
WuR CATEGORIZATION BASED ON FREQUENCY USAGE

Band	Reference No.
sub-GHz	[85], [37], [33], [67], [50], [74], [51], [52], [53], **[54]** , [55], **[40]** [70], [81], [64], [78], [63], **[57]** , **[80]**
2.4 GHz	[88], [61], [65], [90], [68], [73], [75], [39], [89], [77], [56], [82], [83], [84], **[80]**
5 GHz	**[79]**
60 GHz	**[69]** , **[72]**
Others	**[58]** , **[71]** , [86], [87], [59], [60], [62]

2) Operating Frequency: Another layer of complexity is added when considering the transmission frequency of the WuR. Further, if the WuR and the main data transceiver are using different frequencies, each requires a separate antenna for signal detection and separate matching networks. Moreover, the choice of the operating frequency for WuRx is critical as it determines the size of the antenna and the operational range of the system as a whole.

The sub-GHz WuRx presented by Spenza *et al.* [54] consumes 1.276 μW in listening mode. The receiver uses OOK modulation and is made of four main building blocks: a matching network, an envelope detector followed by a comparator and a preamble detector. At the receiver end, the output from the preamble detector is used to interrupt an on-board 8-bit PIC12LF1552 MCU that performs address matching and triggers the main sensor node when a valid wake-up address is received. This sub-GHz WuRx provides high sensitivity and data rate of -55 dBm and 100 kbps respectively, while achieving the maximum wake-up range of 45 m. This design is further improved by Magno *et al.* [40], which achieves power consumption in listening mode of 0.152 μW at 32 dBm sensitivity and 1.196 μW for the -55 dBm version. This particular WuRx has achieved an interesting communication range of up to 50 m and offers data rate of 10 kbps.

Multi-band WuRs have also been exploited to increase the flexibility and to allow interoperability between different frequencies used in WSNs. Robert *et al.* [57] propose an ultra-low power WuRx for indoor/outdoor asset tracking systems that consumes only 5 μW. Authors have developed a tag module that contains a transmitter and two WuRxs integrated in one module. The 434 MHz WuRx is intended for indoor localization, and the 868 MHz WuRx and transmitter are used for the data exchange with the gateways for outdoor localization. The WuRx continuously scans the channel for any predefined wake-up sequences. As soon as the received sequences matches to the reference sequence, a digital control signal is generated immediately to trigger the sensor node. In addition, the proposed WuRx also provides a received signal strength indicator (RSSI) value of the received WuS with 3 bits quantization. A similar prototype for asset tracking applications has also been reported in [80]. The Fraunhofer WakeUp-Receiver [80], which is based on 130-nm CMOS technology, operates in the 868 MHz and 2.4 GHz frequency bands and features -80 dBm sensitivity with 16-bit selective wake-up ID. At a data rate of 1 kbps this prototype consumes 7.5 μW of power with response time of 30.3 ms. However, no detailed operational communication range tests or complete WuR system design is provided.

TABLE IV
WuR FEATURING ADDRESS DECODING

Technique	Reference No.
MCU	[58], **[33]** , [52], [54], **[55]** , [40], [73]
Correlator	**[67]** , **[74]** , [78], **[88]** , [68], [82], [76], [89]
AS3930	**[37]** , [50], [51], [53], [87], [56]
Others	[70], **[63]** , [81], [39]

To achieve relatively high date rates, a WuRx operating in millimeter-wave band (60 GHz) for short-range applications is proposed in [69]. This duty cycled WuR consists of a 4-path phase array transmitter and a 4-path receiver. By applying OOK modulation for switching the biasing of power amplifiers a 1 Gbps data rate is attained. The WuRx side is built of an injection-locking ring oscillator (ILRO), a frequency mixer and a low pass filter. The performance of this receiver is evaluated in simulations and has achieved a power consumption of 230 μW with sensitivity of -62 dBm ranging up to 0.2 m. Instead, Wada *et al.* [72] presented a first successful WuRx prototype operating at 60 GHz. To achieve low power consumption, a power reduction circuit has been implemented that turns off the injection locking oscillator when there is no WuS detected. The fabricated WuRx has a high sensitivity of -68 dBm for a 350 kbps OOK WuS while consuming only 9 μW from a 1.5 V supply. Another WuRx that operates at 5.8 GHz has been reported in [79] but has lower sensitivity of -44 dBm. Note that for the latter two designs, the authors have not published any operational distance.

There are also few WuR designs for WBAN applications that use very low frequency for communication. One of the advantages of operating at lower frequency bands is that it enables lower signal attenuation and interference than the traditional operating bands such as 2.4 GHz. Cho *et al.* [71] proposed the WuRx prototype targeting WBAN applications while operating at 45 MHz. The proposed WuRx uses ILRO instead of RF amplifier to reduce power consumption. The WuS is modulated using Frequency Shift Keying (FSK) and is demodulated by a low power Phase Locked Loop (PLL) demodulator. This prototype features a receiver sensitivity of -62.7 dBm with data rate of 200 kbps while consuming as low as 37.5 μW from a 0.7 V supply in an active mode.

Recently, Petäjäjärvi *et al.* [58] proposed a 28 MHz always on WuR design based on super-regenerative principle for human body communications. To achieve low energy consumption and high sensitivity, the WuR uses loose synchronization and employs self-quenching while operating at 1.25 kbps. With real-life experiments the proposed designed consumes 40μW and achieved receiver sensitivity of -97 dBm.

3) Address Decoding: Next, adding node address decoding capability to the WuRx requires additional components at the RF back-end. Usually, a low power micro-controller (MCU)

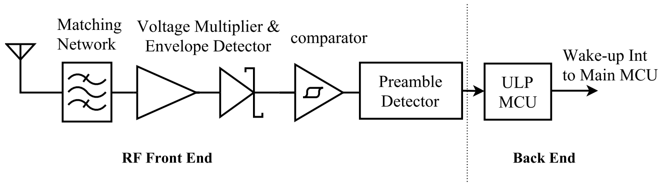


Fig. 8. Wake-up receiver employing an ultra-low power MCU for address decoding and interrupt generation.

or correlator is employed for decoding. However, this comes with some trade-offs, highlighted in this section.

Some WuR designs use a secondary, dedicated low-power micro-controller to decode the address code. An example is shown in Fig. 8, illustrating the integration of low power MCUs with WuR prototypes. As will be discussed later, this extra hardware contributes to energy overhead when used for address decoding.

Using a separate MCU for address decoding and interference filtering is reported in [33]. In this prototype, authors have integrated a PIC12F683 MCU to detect and decode a WuS after signal rectification and amplification, and notify the more powerful AT-mega128L processor of the main node through an interrupt. Due to intervention of this extra PIC12F683 MCU, the overall power consumption of the WuRx increases from 171 μW in listening mode to 819 μW at 3 V when used for address decoding. The proposed prototype was only able to communicate up to 2 m with receiver sensitivity of -51 dBm at data rate of 0.86 kbps using OOK modulation. Another prototype with similar communication range is presented by Bdiri and Derbel [55], but has lower power consumption of 0.69 μW operating in 868 MHz band. Authors have also compared two different WuS decoding techniques, one with MCU and the other using AS3932 (a detailed discussion of the AS323X series will follow at the end of this subsection). The results indicate that using AS3932 for address decoding leads to an additional power consumption of 3.9 μW than the MCU.

Other designs that exploit MCU for address decoding while achieving power consumption below 15 μW can be found in [52] and [73]. However, these designs do not provide any detail on operational distance that can be achieved with these WuRxs.

Instead of using MCUs for address decoding, an energy efficient way is to use correlator circuit for address matching. In the correlator circuit, the node address is stored in the reference signal buffer and the input bits from the WuS are correlated against the reference signal. When a new bit is available, all the samples are shifted one position in the correlator and are compared to the pre-stored one. If the stored and the incoming bits are a match, the wake-up interrupt pin is asserted. Fig. 9 depicts a simple "matched filter" based parallel correlator concept used to decode address in a WuS.

Von der Mark and Boeck [88] simulated one of the first correlator based approaches for decoding node address in a WuRx system and features sensitivity of -50 dBm. The wake-up circuit is composed of a 2.4 GHz matching network, an envelope detector, and low noise amplifier. The output signal from the amplifier is then fed into the correlator circuit to compare the signal to a predefined sequence. However, no values have been reported for power consumption, data rate or WuRx communication range.

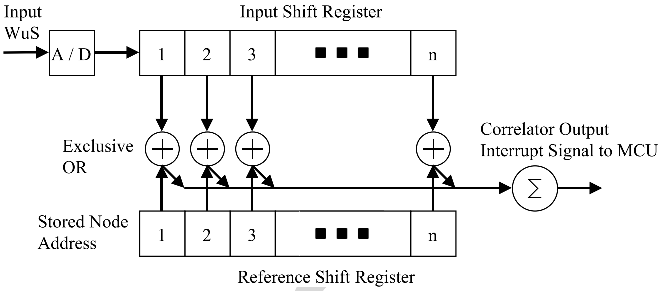


Fig. 9. Node address comparison using "matched filter" correlation detector.

Hambeck *et al.* [67] presented a complete prototype of WuRx employing a 64-bit mixed signal correlator for address matching. At 868 MHz, the design features a receiver sensitivity of -71 dBm and an outstanding measured free-space radio link distance of up to 304 m at transmission power of 6.4 dBm. At this conditions, the WuRx dissipates only 2.4 μW at supply voltage of 1 V.

Milosiu *et al.* [74] presented a 31-bit correlator based WuRx with scalable data rate and -83 dBm sensitivity. The prototype is fabricated in a 130-nm CMOS technology and requires 4.75 μW from a 2.5 V supply at a data rate of 128 bps. Compared to the other WuRx prototypes found so far in the literature, the proposed receiver has obtained the longest line-of-sight communication range of 1200 m for a transmit power of 10 mW. Recently, authors have also proposed a 2.4 GHz version of the OOK WuRx that obtains a power consumption of 7.25 μW with reaction time of 30 ms. However, no details on the receiver range is provided. Other low power designs have also been reported in [68] obtaining power consumption below 3 μW.

There are many proposals in the literature where authors have also resorted to a commercially available WuRx chip for address decoding into their prototypes [36], [37], [51], [53], [55], [87]. The AS393X series from Austria Microsystems [91] is a 3D low-power low-frequency Amplitude Shift Keying (ASK) WuRx capable of generating a wake-up interrupt upon detection of signal at a carrier frequency between 15-150 kHz. The AS393X also allows duty cycling the WuRx in order to save energy and includes an integrated correlator to implement a 16 bit or 32 bit wake-up address decoding scheme. This WuRx has maximum sensitivity of -69 dBm with current consumption varying from 1.7 μA up to 12 μA at 3 V power supply. With these characteristics, the AS393X has average performance compared to other experimental WuR prototypes found in the literature.

Sutton *et al.* [37] presented the first practical application of WuRx that can be used both for initiating the communication and as a full data radio. The OOK WuR transceiver is designed using the off-the-shelf components and leverages AS3930 ASK receiver for address decoding. The CC110L

TABLE V
VARIOUS WUS MODULATION TECHNIQUES

Modulation	Reference No.
OOK	[86], [85], [59], [60], [62], [61], [75], [77], [83], [69], [72], [66], [70], [37], [50], [51], [53], [87], [56], [74], [88], [68], [82], [76], [89], [39], [58], [33], [54], [55], **[40]** , [73], [81], **[84]** , [67]
ASK	[90], [79], [63], [52]
FSK	[71], **[64]** , [78], [84]
Others	[65]

transceiver is used as a WuTx and shares the same antenna with the WuRx module. The OOK receiver is able to receive a 16-bit data packet at a maximum data rate of 8.192 kbps, and features an ultra-low power consumption of 8.1 μW measured at 3 V. The OOK receiver sensitivity is approximately -52 dBm and achieves a 30 m line-of-sight communication range in an outdoor field.

Oller *et al.* [53] proposed WuRx incorporating AS3933 for IEEE802.11-enabled wireless access points. This prototype features a WuRx sensitivity of -52 dBm and the total power consumed by the design is 10.8 μW in sleep mode and 24 μW in an active mode with address decoding. Similar wake-up range of up to 40 m has been observed making these prototypes suitable for implementation that require long range communication with minimum power consumption without relying on MCU for address decoding.

Microsemi based ZL70103 [92] is another off-the-shelf transceiver chip that incorporates a WuRx designed for implantable medical devices. The out-of-band WuRx operates at 2.45 GHz with an average current consumption of 290 nA while sniffing the channel once a second. It allows to initiate the communication between the implanted device and the base station transceiver using specially coded WuS from the 2.45 GHz base station. So far, none of the prototypes presented in this survey use ZL70103, however it is an interesting option for BAN applications.

Other address decoding techniques using Bloom filters [63], shift registers [81], flip-flops, and filter banks [39] have also been exploited. Takiguchi *et al.* [63] have simulated a Bloom filter based wakeup mechanism for WuRxs. A node identifier-matching mechanism uses Bloom filter implemented with a simple circuit that only uses an AND circuit. For a bit rate of 40 kbps, the listening power consumption of the receiver is 12.4 μW and in an active state the circuit consumes 368.1 μW from a 1.8 V supply.

4) WuS Modulation Technique: Circuit complexity and reproducibility are the key factors that allow designers to tune and simplify WuRs enabling faster prototyping. Nevertheless, this is dependent on the modulation technique used for WuS transmission, the architecture of RF front- and back-end, and the choice of frequency. To meet the requirement of ultra-low power consumption, various modulation schemes such as on/off keying (OOK), Amplitude shift keying (ASK), or Frequency shift keying (FSK) have been exploited for the wake up signals.

TABLE VI
TECHNOLOGY UTILIZED FOR PASSIVE WUR

Technology	Reference No.
Discrete	**[93]**
CMOS	[94], **[95]** , [96], **[97]** , **[98]** , [99]
RFID	**[100]** , **[101]** , **[102]**

As seen from Table V, most of the WuR designs have modulated RF signal using OOK before reception by the wake-up receiver. In OOK modulation scheme the signal information is delivered using '1's or '0's. The source node transmits a large amplitude carrier when it wants to send a '1' and nothing is send for '0', i.e., the transmitter is turned off. Thus, allowing systems to save on transmit power when (not) sending '0's. On the receiver side this signal is sensed by the rising edge of the digital signal from low to high indicating that a valid signal has been received via the antenna. This has enabled OOK hardware implementations to be relatively straightforward due to their low implementation cost for battery-operated applications. Usually, few discrete components are enough to construct OOK signal detection circuitry as outlined in [38] and [54]. The super-generative [71], [72], tuned RF [40], [53], [59], or uncertain-IF architectures [75], [89] have been popular solutions to demodulate an OOK signal. In [40], the WuRx consumed 1.2 μW and achieved a sensitivity of -55 dBm at a data rate of 10 kbps to demodulate a 868 MHz OOK signal.

ASK is another popular modulation technique used by WuR hardware designers. Similar to OOK, the information in ASK is also transmitted using '1's or '0's. However, instead of keeping the transmitter off when indicating bit '0', it transmits small amplitude carrier in its simplest form.

For FSK demodulation, WuRxs are based on frequency discrimination architecture. In [64], the WuRx consumes 2700 μW to demodulate a 0.915 MHz FSK signal. The overall receiver sensitivity is -89 dBm at a data rate of 45 kbps.

Most of the designs surveyed in this paper are compatible with only one modulation technique. Therefore, to make a WuRx compatible with other types of signals, Taris *et al.* [84] proposed a first dual modulation based WuRx. This proof of concept features an LC oscillator coupled with an envelope detector implemented in a 65 nm CMOS technology. The circuit consumes 120 μW, and properly demodulates OOK and FSK modulated signals at 2.4 GHz with data rate up to 500 kbps.

Although, ASK offers better noise immunity compared to OOK at a lower cost than FSK, it has higher power consumption demand than OOK based WuRxs (refer to Table VIII and Fig. 13).

B. Passive Wake-Up Radios

This section discusses prototypes that harvest and power the wake-up circuitry entirely from the RF signal. In this way, passive WuRxs have the advantage of not consuming any energy from the node battery making the design energy neutral.

The first proof-of-concept passive WuRx design operating at a frequency of 433 MHz was presented by Gu and Stankovic in 2005 [93]. The WuRx is powered using radio signals and is able to trigger a wake-up interrupt once enough energy has been harvested and stored on the capacitor. The proposed WuRx uses a charge pump approach consisting of capacitors and zero-bias Schottky diodes acting as a voltage multiplier and a radio trigger circuit. This WuRx also features the addressing capability by transmitting the WuS at different frequencies to activate the targeted node, reaching an operating range of around 3 m. The power consumption of the WuRx in idle mode (i.e., while harvesting energy from the WuS) is 145 μW , and the design was only evaluated through SPICE circuit simulations.

Another battery-less WuRx operating at 900 MHz band was proposed in [95]. This passive CMOS chip consists of an RF front end and a digital baseband with non volatile memory. The radio block includes a voltage multiplier for rectifying and amplifying the RF energy, a voltage limiter, demodulator and modulator circuits, and a ring oscillator. Authors have designed the voltage multiplier by cascading 4-stage voltage doublers using Schottky diodes and capacitors. Using ASK modulation technique, the prototype achieved a sensitivity of -17 dBm with power consumption of 2.64 μW. However, no details regarding the communication range and data rate are provided.

Kamalinejad *et al.* [97] presented a passive 868 MHz WuRx front end that also harvests energy from the RF signal. The building blocks consist of an antenna, matching network, voltage multiplier and data slicer (comparator and the reference generator). An RF-to-DC converter is used to produce the envelope of the OOK WuS and converts the RF signal to a DC voltage that is used to power the data slicer circuitry. A fraction of this DC output is then compared with the generated reference to produce the wake-up interrupt signal. Using simulations, the proposed design exhibits a sensitivity of -33 dBm and 100 kbps data rate without any node addressing capability. In turn, Zgaren *et al.* [98] took the idea of Kamalinejad *et al.* [97] and have proposed a passive WuRx prototype for implantable devices operating in 902-925 MHz band. This prototype has a power dissipation of 0.2 μW for a data rate of 100 kbps at -53 dBm sensitivity. However, the latter design is only evaluated using simulations. Other passive WuRxs that are based on CMOS technology can be found in [94], [96], and [99]

Ba *et al.* [102] proposed a passive RFID device called WISP-Mote by combining a Wireless Identification and Sensing Platform (WISP) to a Tmote Sky sensor node. WISP is powered wirelessly by an off-the-shelf UHF RFID reader to generate an external interrupt to a Tmote Sky, achieving communication range of up to 5 m. Upon successful activation, WISP transmits the sensor data using the main node's 2.4 GHz CC2420 transceiver. WISP supports both broadcast and ID-based wake-ups.

Passive RFID based systems usually have a communication range only up to few meters, thus making it difficult to implement a multi-hop sensor network. Therefore, to realize a multi-hop wake-up using RFID technology, Chen *et al.* [100] proposed an enhanced version of WISP-Mote with energy harvesting capabilities called Multi-hop-Range EnhAnCing energy Harvester-Mote (MH-REACH-Mote). MH-REACH-Mote is equipped with both a WuTx and a passive WuRx. The WuRx side is same as WISP-Mote while UHF RFID reader has been used as the WuTx providing an option for an addressable wake-up with high transmission power. This prototype achieved the maximum wake-up range of 9.4 m when the WuS was transmitted for 10s. Donno *et al.* [101] also proposed a passive WuRx prototype using commercial 868 MHz UHF RFID tag and RFID energy harvester for achieving long distances. Authors implemented a wake-up strategy called Enhanced Write Wake Up (E-WWU) that supports both broadcast communication and node addressing achieving a range of 22 m with transmission power of 30 dBm. The WuRx side consumes 54 μW for receiving and decoding the WuS.

TABLE VII
SEMI-ACTIVE WUR DESIGNS

Technology	**Reference No.**
Discrete	**[36]** , **[103]** , **[104]** , **[105]** , **[38]** , [106], [107]
CMOS	[108], [109], [110], **[111]** , [112], [113], [114], **[115]** , **[116]** , [117], [118], **[32]**
RFID	**[119]**

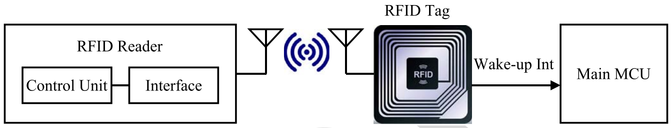


Fig. 10. RFID-based Wake-up receiver prototype [102].

From the above designs, it is evident that CMOS technology is more popular for implementing passive WuRxs due to its low power consumption. RFID has also been utilized since it already provides energy harvesting capabilities thus reducing the implementation time.

C. Semi-Active Wake-Up Radios

To operate in the nano-Watt power range, the majority of the proposed design approaches are semi-active, in which only a few components of the receiver front-end are battery powered while the rest of the components are fully passive. Using passive circuitry allows reducing the power consumption, but at the price of short communication range and reduced receiver sensitivities. For the radio front-end, the most common approach is to implement an envelope detector using passive components such as Schottky diodes, MOSFETs or ICs followed by the active components such as correlators and comparators to generate an interrupt to the main MCU. Next, we present WuR prototypes that utilize such architecture.

Malinowski *et al.* [119] reported the first "quasi-passive wake-up" system utilizing RFID technology called CargoNet. CargoNet employs a 300 MHz RFID tag to trigger an ultra-low power MSP430 based sensor node. The WuS detector circuit consists of an LC tank with an autotransformer for amplifying the signal received at the antenna followed by an envelope detector and micro-power amplifier for voltage gain. After the main sensor node is activated, data is communicated using a 2.4 GHz CC2500 transceiver. The proposed WuRx design consumes 2.8 μW in listening mode. The average power consumption of CargoNet is 23.7 μW when the node is active and receiving the data packet via the main transceiver. At maximum sensitivity of -65 dBm, the WuRx is able to detect an OOK modulated WuS up to a distance of 8 m.

Ansari *et al.* [38] presented a radio triggered wake-up circuit attached to a TelosB node and exploited its main MSP430 MCU for address decoding. The WuTx uses an additional out-of-band 868 MHz CC1000 transceiver for generating WuS using Pulse Interval Encoding (PIE) scheme and a frequency amplifier for communication range extension. The main buildings blocks include an impedance matching network, a voltage multiplier and a digital comparator interfaced to the main MCU. The matching network is constructed using discrete components such as capacitors and inductors while the 5-stage voltage multiplier uses RF Schottky diodes. The MCU tracks the low-to-high transitions and the time intervals between the PIE signal to successfully decode the data. In case the wake-up packet is not addressed to the node, it switches back to the sleep mode. Otherwise, the node triggers its main CC2420 transceiver for data exchange. The WuRx in listening mode consumes only 2.628 μW and the micro-controller consumes 1020 μW when it switches from sleep to active mode for address decoding. Empirical measurements using simulation shows that the proposed WuRx has an operating range of 10 m for the 500μW transmission power.

Le-Huy and Roy [32] also simulated a semi-active WuRx that uses correlator as a decoder. This work has become one of the reference designs for several newer proposals, since authors have outlined the complete steps from signal detection to address comparison. The proposed architecture consists of a shared antenna between the WuRx and the main transceiver, impedance matching network and zero-bias Schottky diode based envelope detector. It is followed by an address decoder circuit that has three subsystems: the amplifier stage, the PWM demodulator and the correlator circuit consisting of shift register and a logic comparator. The power consumption of the proposed architecture is 19 μW at a data rate of 50kbps with receiver sensitivity of -53 dBm. Using Pulse Width Modulation scheme, the receiver exhibits a maximum range of 5 m for 2.4 GHz band.

Ammar *et al.* [103] also proposed a semi-active 868 MHz WuRx that uses Flip Flops for address decoding and dissipates only 13.41 μW. However, this design is only evaluated using simulations. Other simulated designs based on semi-active WuRxs can be found in [105], [109], [110], and [118].

Gamm *et al.* [36] proposed the first in-band sub-Carrier modulation WuRx system based on AS3932 (Fig. 11). In the wake-up mode the WuS is directed to the AS3932 WuRx for envelope and address decoding after impedance matching and demodulation of OOK signal. First, AS3932 extracts the 125 KHz signal from the 868 MHz WuS and then the original data is decoded for address comparison. Once the address is matched, the main node is triggered. Afterwards, an antenna switch is utilized to bypass the WuRx and the data exchange takes place using the main CC1101 transceiver. The main radio is also utilized as a WuTx to generate the WuS, thus the first complete WuR transceiver. The WuRx circuitry is supplied with 3 V battery and has an active power consumption of 7.8 μW while the total node consumption is 44 mW. For an output power of 11 dBm at the WuTx, the maximum wake-up distance was 45 m at a data rate of 250 kbps and sensitivity level of -52 dBm. The design by Gamm *et al.* [36] has become the starting point for other AS393X based WuR systems such as the ones presented in [50], [53], and [56].

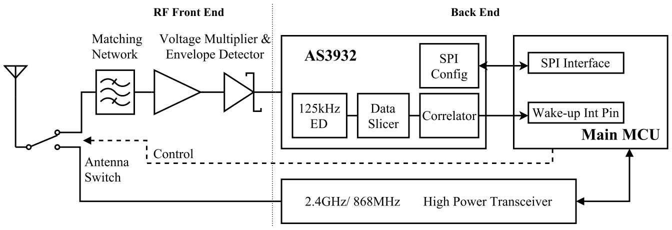


Fig. 11. Wake-up receiver prototype utilizing Austria Micro Systems AS393x WuRx [36].

The most energy efficient semi-active WuRx proposed to-date is presented by Roberts and Wentzloff [111]. The energy is harvested from the RF signal and then the received voltage is boosted using resonant tank before supplied to the active part of the circuit. This 915 MHz band WuRx achieved a communication range of 1.2 m at transmission power of 0 dBm. The whole CMOS based WuRx provides a data rate of 100 kbps using OOK modulation while consuming only 98 nW in active state. However, the WuRx does not support node addressing as per the implementation.

Yet another ultra-low power WuRx intended for WBAN is presented in [104]. The proposed design uses Gaussian On-Off Keying (GOOK) and Pulse Width modulation (PWM) for decoding and encoding the preamble signal, respectively. This receiver has higher power consumption of 2.67 μW than that proposed by Roberts and Wentzloff [111] in listening mode, but achieves a longer communication range of 10 m for WuTx output power of 10 dBm. The WuRx also operates in a sub-GHz frequency band (433 MHz) and has receiver sensitivity of -51 dBm. The address decoding is handled by the MCU and the authors have not provided any details of its related power consumption.

To increase the flexibility of WuR, multi-band WuRs have also been exploited to allow interoperability between different frequencies used in WSNs. Huang *et al.* [115] propose a radio-triggered WuRx able to operate selectively at 915 MHz and 2.4 GHz band. After input matching, an envelope detector suppresses the fundamental tone to the required frequency followed by a baseband amplifier for filtering and amplifying the WuS. This WuRx consumes 51 μW for 100 kbps OOK modulation featuring receiver sensitivity of -75 dBm in the 915 MHz band and -64 dBm in 2.4 GHz band, respectively.

Oh *et al.* [116] presented a tri-band 116 nW WuRx with 31-bit Correlator with interference rejection capabilities.

The WuRx front end operates in the 402 MHz MICS band and the 915 MHz and 2.4 GHz ISM band with sensitivities of -45.5 dBm, -43.4 dBm and -43.2 dBm, respectively. The chip consists of an input matching network for filtering and boosting the incoming WuS and a 30-stage passive rectifier for down-converting the RF signal to baseband, which is then sensed by a comparator. Finally, a bank of 124 correlators is implemented to compare the wake-up sequences with a programmable wake-up code. The wake-up interrupt is generated only when a correlation value exceeds a user-programmable threshold.

Recently, another dual-band WuRx that operates in 868 MHz and 2.4 GHz band has been proposed in [105]. The WuRx front end consists of a dual-band antenna and matching network with a passive envelope detector. The back-end consists of an interrupt/data generator and an ultra-low power micro-controller for address decoding and generating interrupt to the sensor node. The receiver is tuned to use OOK modulation for WuS with sensitivity of -53.4 dBm and -45.2 dBm at 868 MHz and 2.45 GHz, respectively. Simulation results demonstrate that the proposed solution consumes 1.276 μW while listening the channel and this power consumption increases to 70.6 μW when the MCU is decoding the address with supply voltage of 1.8 V.

D. Non-RF Based WuRs

While RF based WuRs have been most widely researched, some authors have proposed an unconventional method to communicate with the WuRx by exploiting different transmitting mediums like optical or ultrasonic signals. For this reason it is quite inappropriate to call such devices WuR, but still some solutions are interesting and expose characteristics that are comparable with RF based WuRs discussed so far. In fact the communication range that could be achieved with these type of wake-up transceivers are similar to typical RF based WuRs while also exhibiting similar power demands. The two main drawbacks are that some of these devices require directionality and/or line-of-sight (LOS) communication between transmitter and receiver, making them inappropriate for some applications. The complete list of all the WuRs in this category is presented in Table IX.

Hakkinen and Vanhala [120] proposed one of the earliest designs where infrared is utilized to transmit WuS. The WuTx is basically an IR LED that is switched on and off by the micro-controller. On the WuRx side, a photo-detector is used for receiving the signal and a transimpedence amplifier converts this signal into voltage to generate an interrupt. It achieves operational range of up to 30 m with an IR remote controller by matching its carrier frequency with the WuRx. The prototype consumes 12 μW when listening for the WuS at a supply of 3 V. Unfortunately, the wake-up circuit is very sensitive to external light and is vulnerable to noise while requiring direct LOS between nodes.

The proposal by Mathews *et al.* [48] utilizes Free Space Optical (FSO) as a secondary wake-up channel. The power consumption of the proposed FSO WuRx is 317 μW in listening mode and attains a LOS range of 15 m at a transmission power of 16.5 mW. Due to low gain bandwidth of the operational amplifiers, the system suffers from low data rate of 2 kbps. Optical based designs implicitly feature node addressing through directional communication, however, it is not clear how this design would perform when the nodes are not perfectly aligned and how to communicate with multiple nodes, if required.

Another optical based WuRx is presented in [49] called Free-space Low-Power optical Wake-up and has an ultra low power of only 695 pW in standby mode and 12.2 nW in active mode. The WuR supports three different light sources for extending communication range. Using 0.5 W LED the wake-up range is 0.2 m, 6 m with 3 W LED with focus and extends to 50 m when a 3 mW green laser is utilized as WuTx. In contrast to [48], FLOW features a 16-bit node addressing capability. However, similar to [48], the WuR system requires direct LOS for transmitting WuS and supports very low bit rate of 91 bps. Moreover, to achieve long range communication, proper physical alignment between the optical WuTx and WuRx is also required.

Sánchez *et al.* [47] have presented an asynchronous acoustic-triggered wake-up modem for underwater sensor networks. Using this technique, the WuRx is programmed to react to acoustic signals at a certain frequency, reactivating the node if needed. The WuRx consumption is 10 μW in listening mode. The authors have also integrated AS3933 for 16-bit node address recognition. With a transmission power of 108 mW, an underwater communication range of 240 m has been achieved.

An ultrasonic WuRx working at 40.6 kHz is proposed in [44]. It uses piezoelectric transducer that converts the mechanical energy into electrical energy for generating wake-up interrupts. The design is based on heterodyne architecture and the overall receiver power consumption is 4.8 μW in listening mode. When exciting the transmitter with an electrical signal power of 16 μW, it achieved an operational range of 8.6 m. However, the WuRx has very low bit rate of 250 bps. Another prototype using ultrasonic signals is presented by Lattanzi *et al.* [45]. Unlike [44], this design supports out-of-band addressing scheme for selective awakening. It uses off-the-shelf components and requires 1.748 μW in listening state and around 14 μW when active. This design is suitable for ranging applications that require distance up to 10 m. The WuTx takes 0.5s to transmit an 8-bit address and requires 75 μW of power at bit rate of 16 bps.

The design by Hoflinger *et al.* [46] presents an acoustic WuRx operating at 18 kHz for controlling devices and appliances at home. The audio signal is sent using a smartphone speaker and a micro-electromechanical system (MEMS) microphone is used to detect the audio signal on the WuRx. The microphone transducer converts this acoustic signal into an electrical signal, which is then fed into AS3933 WuRx IC that detects a valid frequency of 18 kHz and triggers the micro-controller. A wake-up range of 7.5 m was achieved using this setup. The WuRx consumes 56 μW in listening mode while the consumption hikes to 440 μW in active state when receiving the signal using PWM modulation. This design was further improved in [121], which operates at 20 kHz audio signals and features node addressing. To reduce the power consumption compared to [46], the power amplifier and the microphone are duty cycled using the micro-controller. Using this technique, the proposed design attains a power consumption of 45 μW in listening mode and 420 μW in active mode. An average wake-up range of 10 m using smart-phone as a sender was achieved.

Recently, Carrascal *et al.* [122] have developed a visible light communication (VLC) based WuR system. This system uses an off-the-shelf indoor solar panel as a receptor and energy harvester to power the WuRx. The WuRx is also coupled with AS3933. At the transmitter side, a 10 W LED is modulated using OOK at a frequency of 21 kHz to transmit WuS. In an indoor environment, with short bit duration the prototype achieved 7 m range while with longer bit duration maximum achievable range was 14 m. This VLC based WuR consumes 19.2 μW in listening mode and ~95 μW when receiving and decoding the WuS. The transmission power required to achieve the above range was 87.9 mW at a data rate of 1.12 kbps. The proposed system is suitable for indoor applications only and allows to harvest energy from the indoor lights for energy-autonomous operation of the WuRx.

E. Summary

In Section III, we considered different physical layer characteristics of wake-up receivers, each designed and tested in separate ways. We next discuss some of the advantages, disadvantages, and features for each category.

From the application point of view, RFID-based WuR systems are suited for mid-range applications such as health monitoring, inventory monitoring, or environmental applications [102]. Nonetheless, the maximum communication range achieved so far has been 30 m using an active RFID tag [90]. As active RFID tags are costly and require more power, such WuR designs may not be suitable for applications that require extended lifetime with minimum maintenance. Moreover, the communication range of RFID devices are related to antennae size: the bigger the antenna the more power can be transmitted thus the longer the range. For WuR based applications that demand small form factor, this could be a hindrance and may force designers to opt for other technologies such as system-on-chip, which may be suitable for a wide range of applications. In addition, for passive RFIDs and EH-WuRxs not all energy is absorbed by the receiving end resulting in a phenomenon known as backscattering. Thus, WuS are transmitted at high power and usually take a few seconds to accumulate and recharge the capacitors for powering up the circuits. This, in turn, affects the wake-up range and the latency of the system as a whole.

Most active WuRs use CMOS technology and a heterodyne approach. While these heterodyne-based WuRs offer superior sensitivity and data rate, most lack node addressing capabilities and information on their operational range. This category of WuR also features the highest power consumption of up to a few milliwatts [87], [89] as the heterodyne approach requires some active components such as IF-amplifiers and mixers. It has also been noticed that some of these designs operate in lower non-ISM bands such as 45 MHz [71] or 1.9 GHz [60] making them inadequate for medical applications. By contrast, lower operation frequency may enable the design of transceivers that consume less power than transceivers in higher frequencies. Moreover, it enhances security compared to traditional wireless technologies for WBAN by making the radio signal more difficult to eavesdrop.

It has also been observed that the use of a secondary MCU for address decoding allows faster prototyping at the receiver back-end. On the other hand, the introduction of this extra hardware adds to the overall power overhead and may not be applicable for applications that have strict power requirements. However, due to advancements in miniaturization, the power consumption of these MCUs has drastically reduced over the years making it possible to integrate with WuRx while still achieving power consumption below 10 μW.

The choice of modulation scheme also affects the overall WuRx performance. If a complex modulation technique like FSK is utilized, this demands complex circuitry at the RF front-end such as the use of active demodulators, mixers, and amplifiers that require extra power. Therefore, simple modulation techniques such as OOK and ASK presents an opportunity to simplify the WuRx circuitry and to achieve low power consumption. Most of the WuRxs reported are compatible with only one of these two modulations. As a consequence, the WuRx architecture implemented in wireless nodes can limit the interoperability with other transmitters.

V. STATISTICAL ANALYSIS

Different components of the WuR design impact its final performance and add to its overall power consumption. In this section, we compare different RF based WuR prototypes designed and tested in terms of power consumption, sensitivity, data rate, communication range and the modulation scheme used, regardless of their specific technology. The numbers presented in this section are the actual numbers reported by the authors of each article. This statistical comparison will then be used as a *guideline* to recommend which prototypes are suitable and meet the requirements of various applications outlined in Section VIII.

A. Modulation Schemes

The main goal of incorporating WuR with typical sensor node is to reduce power consumption. In order to achieve this, the WuR design should be of low power, hence, the modulation complexity should be kept low as well. The higher the modulation complexity, the more stringent requirements for receiver and transmitter in terms of circuit complexity and power.

When comparing this with the state-of-the-art low power WuR summarized in Table VIII, it can be noted that most designs use either envelope detector based On-Off keying (OOK) or non-coherent Frequency-Shift-Keying (FSK). To curb energy consumption by simplifying overall implementation, the designers of the WuR generally favor architectures utilizing OOK modulation schemes. For instance, a simple envelope detector using few diodes and capacitors can be used for signal detection [40], [54], [104]. It is evident from Table VIII that most of the concepts that have power consumption below 10μW are using OOK modulation.

TABLE VIII
RADIO FREQUENCY BASED WAKE-UP RADIO PROTOTYPES

No.	Year	Authors	P.Src	Address	Channel	Mod	Signal Detection	RF Front End	A.D	Tech	S.V [V]	Freq [GHz]	D.R [kbps]	Sens [dBm]	R [m]	Pwr [μW]	Implement
1	2002	Rabaey et al. [59]	Active	-	-	OOK	ANT, MN	LNA	-	CMOS	1	1.9	100	-75	10	380	Simulation
2	2005	Gu et al. [93]	Passive	ID-Based	O-O-B	OOK	ANT, MN	PD, ED, VM, LNA	MF	Discrete	-	0.433	-	-	3	-	Simulation
3	2007	Pletcher et al. [60]	Active	Broadcast	-	OOK	ANT, MN, BAW	ED, LNA,	-	CMOS	0.5	1.9	40	-50	-	65	Prototype
4	2007	Malinowski et al. [119]	Semi-Active	ID-Based	O-O-B	OOK	ANT, MN	ED, LNA, VM	-	RFID	3	0.3	-	-65	8	2.8	Prototype
5	2007	Mark et al. [88]	Active	ID-Based	-	OOK	ANT, MN	ED, LNA,	C	BiCMOS	-	2.4	-	-50	-	-	Simulation
6	2008	Yu et al. [61]	Active	Broadcast	I-B	OOK	MN	ED	-	CMOS	1.8	2.4	100	-75	-	56	Simulation
7	2009	Pletcher et al. [62]	Active	Broadcast	-	OOK	ANT, MN, BAW	ED, M-IF	-	CMOS	0.5	2	100	-72	-	52	Prototype
8	2009	Doorn et al. [33]	Active	ID-Based	I-B	OOK	ANT, MN	LNA	MCU	Discrete	3	0.868	0.862	-51	2	819	Prototype
9	2009	Takiguchi et al. [63]	Active	ID-Based	I-B	ASK	ANT, MN	ED	BF	CMOS	1.8	0.95	40	-36.9	10	368.1	Simulation
10	2009	Lim et al. [112]	Semi-Active	-	-	OOK	ANT, MN	ED, VM	-	CMOS	1.5	2.4	-	-28	-	1.35	Prototype
11	2009	Ansari et al. [38]	Semi-Active	ID-Based	O-O-B	PIE	ANT, MN	ED, VM	MCU	Discrete	3	0.868	0.75	-	10	2.628	Prototype
12	2009	Durante et al. [117]	Semi-Active	ID-Based	-	OOK	ANT, MN	ED, LNA,	MCU	CMOS	1.5	2.4	100	-57	-	12.5	Prototype
13	2009	Le-Huy et al. [32]	Semi-Active	ID-Based	I-B	PWM	ANT, MN	ED, LNA	C	CMOS	1	2.4	50	-53	5	19	Simulation
14	2009	Langevelde et al. [64]	Active	-	-	FSK	ANT	zero-IF, LNA	-	CMOS	1.5	0.915	45	-89	10	2700	Prototype
15	2010	Gamm et al. [36]	Semi-Active	ID-Based	I-B	OOK	ANT,MN	ED	AS	Discrete	3	0.868	250	-52	40	7.8	Prototype
16	2010	Drago et al. [65]	Active	-	-	PPM	ANT, MN	M-IF	-	CMOS	1.2	2.4	500	-82	-	415	Prototype
17	2010	Jurdak et al. [90]	Active	-	O-O-B	ASK	-	RFID Tag	-	RFID	3	2.4	250	-95	30	80	Simulation
18	2010	Huang et al. [115]	Semi-Active	Broadcast	I-B	OOK	ANT,MN	ED, LNA	-	CMOS	1	0.915/2.4	100	-64	-	51	Prototype
19	2011	Chung et al. [95]	Passive	-	-	ASK	ANT	ED, VM, ILRO	-	CMOS	0.8	0.9	-	-17	-	2.64	Prototype
20	2011	Zhang et al. [66]	Active	-	-	OOK	ANT,MN	ED	-	CMOS	1.2	-	200	-	-	3.72	Prototype
21	2011	Hambeck et al. [67]	Active	ID-Based	-	OOK	ANT, SAW	ED, BB	C	CMOS	1.2	0.868	20-200	-71	304	2.4	Prototype
22	2011	Tang et al. [68]	Active	ID-Based	I-B	OOK	ANT, MN	ED, LNA	C	CMOS	-	2.4	100	-82	-	-	Prototype
23	2011	Li et al. [69]	Active	-	-	OOK	ANT	ILRO	-	CMOS	1.2	60	1000000	-62	0.2	230	Simulation
24	2011	Marinkovic et al. [104]	Semi-Active	ID-Based	O-O-B	OOK	ANT,MN	ED, LNA, PD	MCU	Discrete	1.5	0.433	5.5	-51	10	0.27	Prototype
25	2012	Roberts et al. [111]	Semi-Active	-	-	OOK	ANT, MN	ED, LNA	-	CMOS	1.2	0.915	100	-41	1.2	0.098	Prototype
26	2012	Sjoland et al. [109]	Semi-Active	ID-Based	-	FSK	ANT, SAW	LNA, M-IF	1B	CMOS	0.8	2.4	250	-92	-	1000	Simulation
27	2012	Yoon et al. [70]	Active	ID-Based	-	OOK	ANT, MN	ED, LNA, PD	1B	CMOS	1.8	0.9	200	-73	-	1100	Prototype
28	2013	Oller et al. [50]	Active	ID-Based	O-O-B	OOK	ANT, MN	ED, VM, LNA	AS	Discrete	5	0.868	1	-45	13.5	2.67	Prototype
29	2013	Cho et al. [71]	Active	-	-	FSK	ANT	LNA, ILRO	-	CMOS	0.7	0.045	200	-62.7	-	37.5	Prototype
30	2013	Wada et al. [72]	Active	-	-	OOK	ANT, MN	ED, BB,ILRO	-	CMOS	1.5	60	350	-68	-	9	Prototype
31	2013	Francois et al. [73]	Active	ID-Based	-	OOK	ANT,MN	ED, PD	MCU	CMOS	1.2	2.4	250	-	-	5	Simulation
32	2013	Milosiu et al. [74]	Active	ID-Based	-	OOK	ANT,MN	LNA, H	C	CMOS	2.5	0.868	0.128	-83	1200	4.75	Prototype
33	2013	Oh et al. [116]	Semi-Active	-	-	OOK	ANT,MN	ED, VM	C	CMOS	1.2	0.402/0.915/2.4	12.5	-43.2	-	0.116	Prototype
34	2013	Prabhakar et al. [51]	Active	ID-Based	I-B	OOK	ANT, MN	ED, LNA, VM	AS	Discrete	3	0.868	125	-	-	24.9	Prototype
35	2013	Kim et al. [75]	Active	-	-	OOK	ANT	ED, LNA, M-IF, H	-	CMOS	1.8	2.4	100	-60	-	1008	Prototype
36	2013	Boaventura et al. [52]	Active	ID-Based	O-O-B	ASK	ANT, MN	ED, VM	MCU	Discrete	3	0.86	9.6	-35	-	10.8	Prototype
37	2013	Nilsson et al. [99]	Passive	ID-Based	-	OOK	ANT, MN	ED, BB	C	CMOS	1	2.4	200	-47	-	2.3	Prototype
38	2013	Ba et al. [102]	Passive	ID-Based	O-O-B	ASK	-	RFID Tag	MCU	RFID	-	0.9	1pkt/min	-80	<5	-	Prototype
39	2014	Petrioli et al. [39]	Active	ID-Based	I-B	OOK	ANT, MN	ED, LNA	FB	Discrete	1.2	2.4	250	-83	120	1620	Prototype
40	2014	Oller et al. [53]	Active	ID-Based	I-B	OOK	ANT, MN	ED	AS	Discrete	3	0.868	2.7	-53	41	26.4	Prototype
41	2014	Spenza et al. [54]	Active	ID-Based	O-O-B	OOK	ANT, MN	ED, PD, VM	MCU	Discrete	1.8	0.868	100	-55	45	1.276	Prototype
42	2014	Bdiri et al. [55]	Active	ID-Based	O-O-B	OOK	ANT, MN	ED, VM	MCU	Discrete	3	0.868	-	-	2.5	0.69	Prototype
43	2014	Tzschoppe et al. [89]	Active	ID-Based	-	OOK	ANT, MN	ED, LNA, M-IF, VM	COM	BiCMOS	2.5	2.4	-	-44	-	8250	Prototype
44	2014	Patel et al. [76]	Active	ID-Based	-	OOK	ANT, MN	ED, LNA	C	CMOS	0.9	-	-	-	-	63.98	Simulation
45	2014	Bryant et al. [77]	Active	Broadcast	-	OOK	ANT,MN	ED, M-IF, BB	-	CMOS	0.75	2.4	250	-88	-	50	Prototype
46	2014	Abe et al. [78]	Active	ID-Based	-	FSK	ANT, MN	ED, M-IF, LNA	C	CMOS	0.7	0.924	50	-87	-	45.5	Prototype
47	2014	Kamalinejad et al. [97]	Passive	Broadcast	-	OOK	ANT, MN	ED, LNA, VM	-	CMOS	-	0.868	100	-33	-	0.5	Simulation
48	2014	Oller et al. [56]	Active	ID-Based	I-B	OOK	ANT, MN	ED	AS	Discrete	3	2.4	0.9	-52	40	24	Prototype
49	2014	Choi et al. [79]	Active	-	-	ASK	ANT	ED, BB, LNA, M-IF	-	CMOS	3.6	5.8	0.014	-44	-	36	Prototype
50	2014	Donno et al. [101]	Passive	ID-Based	O-O-B	-	ANT, MN	UHF RFID Tag	MCU	RFID	1.8	0.868	-	-	22	54	Prototype
51	2014	Fraunhofer [80]	Active	ID-Based	-	-	ANT, MN	-	-	CMOS	2.5	0.868/2.4	1	-80	-	7.5	Prototype
52	2015	Moazzeni et al. [81]	Active	ID-Based	-	OOK	ANT, MN, SAW	ED, LNA, M-IF	SR	CMOS	1	0.9	200	-78.5	10	22.9	Prototype
53	2015	Milosiu et al. [82]	Active	ID-Based	-	OOK	ANT, MN	ED, LNA, H	C	CMOS	2.5	2.4	1	-80	-	7.25	Prototype
54	2015	Roberts et al. [57]	Active	ID-Based	-	-	-	-	-	Discrete	2.5	0.433/0.868	-	-	-	5	Prototype
55	2015	Zgaren et al. [98]	Passive	-	I-B	OOK	ANT, MN	ED, LNA	-	CMOS	1.2	0.915	100	-53	-	0.2	Prototype
56	2015	Prete et al. [105]	Semi-Active	ID-Based	I-B	OOK	ANT, MN	ED, VM	MCU	Discrete	1.8	0.868/2.4	-	-53	-	1.27	Simulation
57	2015	Shekhar et al. [94]	Passive	-	I-B	-	ANT, MN	ED, VM	-	CMOS	-	2.4	-	-23	-	-	Simulation
58	2015	Sutton et al. [37]	Active	ID-Based	I-B	OOK	ANT, MN	ED, PD, VM	AS	Discrete	3	0.434	8.192	-52	30	8.1	Prototype
59	2015	Salazar et al. [113]	Semi-Active	-	-	OOK	ANT, MN	ED, LNA, M-IF	-	CMOS	0.5	2.4	10	-97	-	99	Prototype
60	2015	Ammar et al. [103]	Semi-Active	ID-Based	-	OOK	ANT, MN	ED, VM, LNA	FF	Discrete	0.9	0.868	100	-54	-	13.41	Simulation
61	2015	Chen et al. [83]	Active	-	-	OOK	ANT, MN	ED, BB, COM	-	CMOS	0.8	2.4	100	-50	-	4.5	Prototype
62	2015	Taris et al. [84]	Active	Broadcast	-	OOK/FSK	ANT, MN	ED, BPF, M-IF, BB	-	CMOS	0.6	2.4	150	-36	-	120	Prototype
63	2015	Wang et al. [108]	Semi-Active	-	-	-	ANT, MN	ED, VM	-	CMOS	-	-	10	-	-	0.05	Simulation
64	2015	Sumanthi et al. [106]	Semi-Active	-	-	OOK	ANT, MN	ED, VM, LNA, PD, COM	-	Discrete	-	0.433	128	-32	-	-	Simulation
65	2015	Chen et al. [100]	Passive	ID-Based	O-O-B	-	-	RFID Tag	AS	RFID	-	0.9	-	-86	9.4	-	Prototype
66	2015	Bdiri et al. [87]	Active	ID-Based	-	OOK	ANT, MN	ED, M-IF	AS	CMOS	2.5	1.5	-	-60	82	5247.5	Prototype
67	2016	Magno et al. [40]	Active	ID-Based	-	OOK	ANT, MN	VM, ED, PD, LNA, COM	MCU	Discrete	1.8	0.868	10	-55	50	1.2	Prototype
68	2016	Shuangming et al. [118]	Semi-Active	ID-Based	-	O-QPSK	ANT, MN	PD	C	CMOS	1.8	2.4	250	-	-	28.2	Simulation
69	2016	Roberts et al. [96]	Passive	ID-Based	-	CDMA	ANT, MN	ED, LNA, COM	C	CMOS	-	2.4	8.192	-56.5	-	0.236	Prototype
70	2016	Hoang et al. [85]	Active	-	-	OOK	ANT, MN	LNA, BPF, BB, COM	-	CMOS	1	0.315	10	-58.5	-	1.36	Simulation
71	2016	Juha et al. [58]	Active	ID-Based	O-O-B	OOK	ANT, MN	ED	-	Discrete	1.5	0.028	1.25	-97	-	40	Prototype
72	2016	Hsieh et al. [114]	Semi-Active	-	O-O-B	OOK	ANT, MN	ED, LPF, LNA, M-IF	-	CMOS	0.45	402-405	50	-55	-	352	Prototype
73	2016	Thanh et al. [110]	Semi-Active	-	-	OOK	ANT, MN	ED, LNA, ILRO, M-IF, COM	-	CMOS	1.2	408	50	-55	-	100	Simulation
74	2016	Polonelli et al. [107]	Semi-Active	ID-Based	-	OOK	ANT, MN	ED, VM, PD, LNA, COM	MCU	Discrete	-	868	-	-35	3	63	Prototype
75	2016	Nikoofard et al. [86]	Active	-	-	OOK	ANT, MN	ED, LNA, BB, COM	-	CMOS	0.5	0.050	1	-60	-	0.0115	Simulation

TABLE IX
NON-RF BASED WAKE-UP RADIO PROTOTYPES

No.	Year	Authors	P.Src	Address	Channel	Mod	Signal Detection	RX Front End	A.D	Medium	S.V [v]	Freq [kHz]	D.R [kbps]	Sens [dBm]	R [m]	Pwr [μW]	Implement
1	2008	Hakkinen et al. [120]	Active	-	O-O-B	OOK	Photo Diode	LNA, BPF, COM	-	Infrared	3	-	-	-	6~30	12	Prototype
2	2010	Mathews et al. [48]	Active	-	O-O-B	OOK	Photo Diode	LNA, C	-	Optical	3.3	-	2	-53	15	317	Prototype
3	2012	Kim et al. [49]	Active	ID-Based	O-O-B	PWM	LED	LED, C	MCU	Optical	1.2	-	0.091	-	0.2~50	0.000695	Prototype
4	2012	Sanchez et al. [47]	Active	ID-Based	O-O-B	OOK	Transducer, MN	BPF	AS3933	Sonar	3.3	85	1	-	240	8.1	Prototype
5	2013	Yadav et al. [44]	Active	-	O-O-B	OOK	Piezoelectric, MN	LNA, M-IF, BB	-	Ultrasonic	0.6	40.6	0.25	-	8.6	4.78	Prototype
6	2013	Lattanzi et al. [45]	Active	ID-Based	O-O-B	OOK	Piezoelectric, MN	LNA, C	MCU	Ultrasonic	2	40	0.016	-10	10	1.748	Prototype
7	2014	Hoflinger et al. [46]	Active	-	O-O-B	PWM	Microphone	LNA	AS3933	Audio	3	18	-	-	7.5	56	Prototype
8	2016	Bannoura et al. [121]	Active	ID-Based	O-O-B	ASK	Microphone	BPF, LNA	AS3934	Audio	3	20	-	-	10	45	Prototype
9	2016	Carrascal et al. [122]	Active	ID-Based	O-O-B	ASK	Solar panel	ED,C	AS3933	VLC	2.4	21	1.12	-	7~14	19.2	Prototype
10	2016	Lim et al. [123]	Active	-	O-O-B	OOK	Photo Diode	PD,COM	-	Optical	-	-	250	-	25	28.1	Prototype

Key:
P.Src-Power Source; **Mod**-Modulation Technique; **RX Front End**-Receiver Front End; **A.D**-Address Decoding Capabilities; **Tech**-Technology Used; **S.V**-Supply Voltage; **Freq**-Frequency; **D.R**-Data Rate; **Sens**-Sensitivity; **R**-Operational Range; **Pwr**-Power Consumption in Active Mode; **Implement**-Implementation; **O-O-B**-Out-of-Band; **I-B**-In-Band; **ANT**-Antenna; **MN**-Matching Network; **PD**-Preamble Detector; **ED**-Envelope Detector; **VM**-Voltage Multiplier; **LNA**-Low Noise Amplifier; **M-IF**-Mixers and IF-Amplifier; **FB**-Filter Bank; **MCU**-Micro-controller Unit; **AS**-AS393X Series; **C**-Correlator; **1B**-1 Bit ADC; **ILRO**-Injection Locking Ring Oscillator; **BF**-Bloom Filter; **MF**-Multiple Frequencies; **BB**-Base Band Amplifier; **SR**-Shift Register; **H**-Heterodyne; **COM**-Comparator; **BAW**-Bulk Acoustic Wave; **SAW**-Surface Acoustic Wave; **FF**-Flip Flop; **BPF**-Band Pass Filter; **VLC**-Visible Light Communication;

Note: Articles that did not provide values for particular information has been stated as (-) in the Tables.

In contrast, the nonlinear nature of envelope detectors make the OOK receivers more susceptible to interference contributing to higher packet error rate and need for retransmission. One can argue that retransmission is expensive in terms of power, but the burden of this is shifted from high power radio to ultra-low power WuR. The advantage of FSK over OOK is that it is more resilient to fading and interference. Therefore, in view of low power WuRx design, either OOK or FSK modulation scheme should be considered.

There are five reported design concepts that differ from above. The concept presented by Le-Huy and Roy [32] uses Pulse-width modulation (PWM) technique since it only requires an integrator with a reset option without increasing the complexity of the receiver architecture. Another benefit of using PWM is that it presents the possibility to control the duty cycle of the transceiver. Shuangming *et al.* [118] use the Offset quadrature phase-shift keying (O-QPSK) to design an ultra low power System-on-Chip (SoC) based baseband processor with wake-up identification receiver consuming only 28.2 μW. The concept by Ansari *et al.* [38] use multi-stage approach for WuSing where CC1000 radio chip is used to perform OOK by turning on and off it's power amplifier. Then the digital data is encoded using Pulse Interval Encoding (PIE) with different time intervals *T*. In order to successfully decode this data sequence, authors utilize MSP430 series micro-controller. A broadband-IF super heterodyne proposal for a crystal-less 2.4 GHz WuRx is presented by Drago *et al.* [65]. The WuS is modulated by means of Pulse Position Modulation (PPM). In order to reduce the power consumption of their design, both the signal front-end and the oscillator are duty-cycled at the pulse level. The WuRx achieves -82 dBm sensitivity and requires up to 415 μW. Recently, Roberts *et al.* [96] have proposed a Bluetooth Low Energy (BLE) WuRx with energy harvesting capability. They have utilized Code division multiple access (CDMA) modulation scheme referred to as Back-channel for encoding and decoding the WuS. Upon signal detection, the information is fed into a baseband processor that correlates the energy levels with a time-based template that matches the sequence of BLE advertising packets to determine the presence of a wake-up message. This CMOS based design was able to achieve sensitivity of -56.5 dBm while consuming only 236 nW.

B. Sensitivity vs. Power Consumption

Fig. 12 shows the comparison between the WuR's power versus sensitivity. It should be noted that these are all custom ultra-low power radios, including radios of different architecture, different data rate, different operating frequencies; none of which is separated in this plot.

Generally, the power consumption of the WuR is related to its sensitivity. With power consumption, in μW, on the y-axis and the sensitivity, in dBm, on the x-axis, two distinct trends can be observed. First, when looking at sensitivity higher than -40 dBm (to the left on the x-axis) it can be seen that there is no direct correlation between the changing sensitivity to the power of the receiver. However, there is a floor around 2 μW suggesting that there is a minimum power requirement for

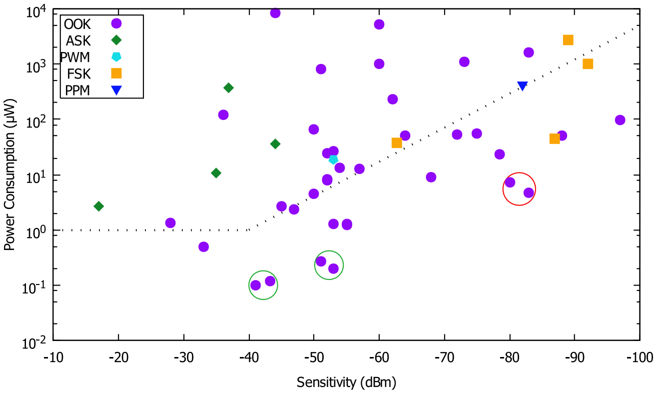


Fig. 12. Sensitivity of low power RF based wake-up receivers vs. Power consumption w.r.t different signal modulation techniques.

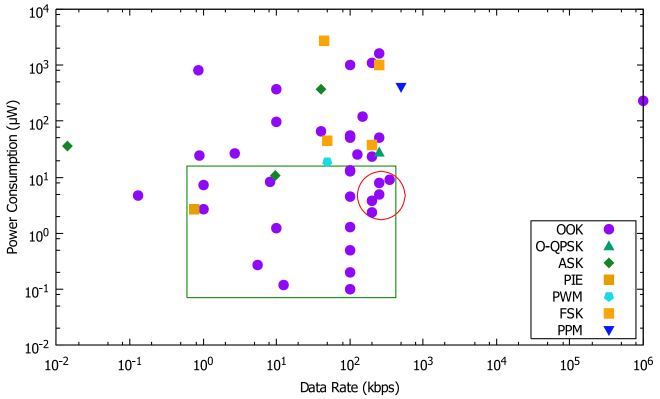


Fig. 13. Data Rate of low power RF based wake-up receivers vs. their Power consumption w.r.t different signal modulation techniques.

the radio regardless of sensitivity. With increasing sensitivity from -40 dBm (to the right on the x-axis) there is a liner trend indicating a correlation between sensitivity and power. It can be seen empirically through slope-fitting that a 20 dBm change in sensitivity results in an approximately 10× change in power consumption. The designs below this slope are regarded as energy efficient as most of them exhibit high sensitivity at low energy cost.

Moreover, as can be seen in Fig. 12, the lowest power consumption that has been achieved so far has been 98 nW [111], but not without trading-off the sensitivity (-41 dBm). This design was able to achieve a communication range of only 1.2 m. Out of 75 prototypes that we have surveyed for RF based WuR for those that power consumption and sensitivity values were provided, only 23 prototypes were able to achieve power consumption below 10 μW, where [86], [111], and [116] reached an outstanding power consumption around 100 nW.

Regarding the requirements for different applications in Table XII, it can be seen that for short-range communication such as WBAN, five WuR prototypes [96], [98], [104], [111], [116] (marked with green circles) fulfill the power consumption and sensitivity requirements. All these prototypes have power consumption below 0.27 μW with sensitivity ranging between -40 dBm to -56 dBm. For mid-range communication (e.g., smart city and metering), only [74], [82] (marked with a red circle) fullfill all these requirements at the same time. Power and sensitivity of these prototypes are 4.75 μW and 7.25 μW, and -83 dBm and -80 dBm, respectively.

For ultra-low power WuR, the knowledge from Fig. 12 is useful for understanding key design trade-offs. For example, most designers [64], [87], [89] try to push the sensitivity as low as possible to achieve better communication range, but this may lead to power-costly design.

In terms of modulation technique, most of these designs utilize OOK modulation. OOK based prototypes have been able to reach the two extreme ends of the power levels, one being the most energy efficient [111] while the other design is not [87]. There are two designs, one based on CDMA [96] and the other using FSK modulation [78] that have also been able to achieve an excellent receiver sensitivity of -56.5 dBm and -87 dBm, respectively with very low power requirements. Both of these prototypes are fabricated using 65nm CMOS process and use correlators for address decoding.

C. Data Rate vs. Power Consumption

Fig. 13 shows the data rate of WuRxs with respect to their power consumption and signal modulation techniques. Since, power is inversely proportional to data rate, it is generally possible to increase the data rate with little power overhead [124], however, communication distance will be short. For example, it does not cost much in terms of power to increase the modulation rate from 1 kbps [50] to 100 kbps [83] in an OOK receiver.

As can be seen, there are fourteen designs that have been able to reach a data rate above 200 kbps. Out of these, five [36], [66], [72], [73], [99] have a power consumption below 10 μW.

From the application perspective, there are few designs [36], [66], [72], [73], [99] (circled in red) that offer high data rate at the same time consuming low power making them suitable for WBAN application scenarios for replacing the high data radio with WuR. Thanks to its high data rate and low power consumption, these WuR utilized as main data radio can have an advantage over duty cycled transceiver in terms of reducing the overall communication delay. One of the prototypes in the millimeter-wave band operating at 60 GHz based on OOK modulation has been designed to achieve very high data rate of up to 1 Gbps [69], however, it may not be applicable for WBAN due to its high power consumption of 230 μW. However, this makes it suitable for wireless personal area network applications that demand short-range of up to 0.2 m with high data rate.

For mid-range applications that require moderate data rates with low power consumption, there are few prototypes (green rectangle) that may be suitable for these scenarios. All these prototypes have data rate between 0.75 kbps to 500 kbps, and power consumption below 12.5 μW.

D. Range and Frequency Usage

So far we have only looked at the modulation technique, receiver sensitivity, and data rate. Another factor that impacts

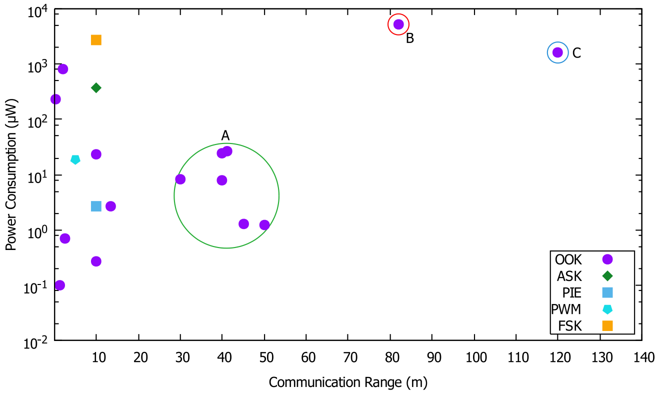


Fig. 14. Communication Range of RF based wake-up receivers vs. their Power consumption w.r.t different signal modulation techniques.

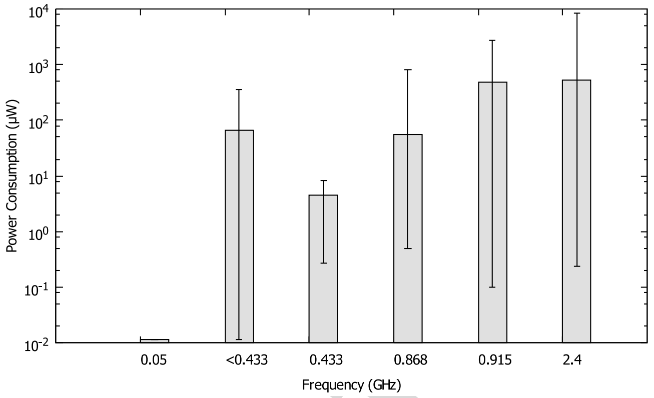


Fig. 15. Frequency selection vs. Power consumption.

the power consumption of wake up radios is the carrier frequency. The choice of the carrier frequency is an important parameter for the wake-up transceiver. Fig. 15 shows the main frequency bands that have been utilized by most of the WuR prototypes together with the min, max and average power consumption. One of the trends that can be observed is that the average power consumption of transceivers increases from sub-GHz band to 2.4 GHz. This is due to the fact that transceiver circuits running at higher frequencies require more current to achieve the same performance as lower frequencies.

From this survey and referring to Table VIII, it can be seen that 25 of the prototypes are based on 2.4 GHz while 32 of them are between 433 MHz and 915 MHz. One of the designs that have achieved an outstanding power consumption of 0.0115 μW operates in 50 MHz [86]. The design is based on CMOS technology and features a data rate of 1kbps with receiver sensitivity of -60dBm. Due to its semi-active design and OOK modulation, this particular prototype managed to surpass state-of-the-art wake-up radios in terms of sensitivity and power trade-off. However, it has only been tested via simulations. Nevertheless, most of the designers have opted to shift from high frequency to sub-GHz as an operating frequency for wake-up receivers. One of the reasons is that at higher frequencies the attenuation rate also increases, i.e., the 2.4 GHz signal weakens faster than a sub-GHz signal. According to the Friis equation, the path loss at 2.4 GHz is 8.5 dB higher than at 900 MHz translating into 2.67 times longer range for 900 MHz transceivers.

Besides the need for higher power for the same link budget, 2.4 GHz band is more prone to interference due to spectrum crunch and devices such as Wi-Fi and Bluetooth operating in the same band. Sub-GHz ISM bands are mostly used for proprietary low-duty-cycle links and are not as likely to interfere with each other. The quieter spectrum means easier transmissions and fewer retries, which is more efficient and saves battery power for wake-up radio based systems.

Furthermore, Fig. 14 shows the maximum achievable communication range reported for different WuR prototypes in terms of their power consumption. It should be noted that we do not take into account prototypes that did not report explicitly the communication range of the WuR. From the application point of view, WuR prototypes with communication range between 30 m to 50 m (labeled as cluster A) [36], [37], [40], [53], [54] satisfy the requirements for mid-range applications. For the WBAN case WuR concepts [36], [66], [72], [73], [99] fulfill the sensitivity, data rate and power requirements, if used as a full data radio. However, if utilized just as a secondary radio for triggering the main node's transceiver, WuR with power consumption below 10 μW should be considered.

E. Summary

The main characteristics of all ultra-low power WuR are sensitivity, data rate, frequency, and power consumption. However, the technology used to design WuR prototypes vary from simple energy detection using discrete components to envelope detection using CMOS, influencing its overall performance. Therefore, for different application requirements the best prototype has to be selected carefully. While some provide high data rate, others are better for high sensitivity or very low power consumption.

It has been observed that to achieve ultra-low-power consumption while maintaining robust operation involves difficult trade-offs between range, data rate, sensitivity, and energy efficiency that must be overcome through a combination of innovative circuit design, novel architectures, and system-level considerations. This section has provided some benchmarking data to help identify what architectures and WuR prototypes might make the most sense given system-level specifications. While optimal implementations depend strongly on the given application, in general the most energy efficient WuR employ low-complexity modulation schemes (e.g., OOK).

VI. MEDIUM ACCESS CONTROL

Major work on WuR technology has been focused on improving hardware components to achieve better power consumption and physical layer communication characteristics. Nevertheless, to fully exploit the technology, it must be coupled with communication protocols, rounding out the system design. We divide our discussion in two parts, first focusing on medium access in this section, then moving up the protocol stack to routing in the next section. In considering MAC,

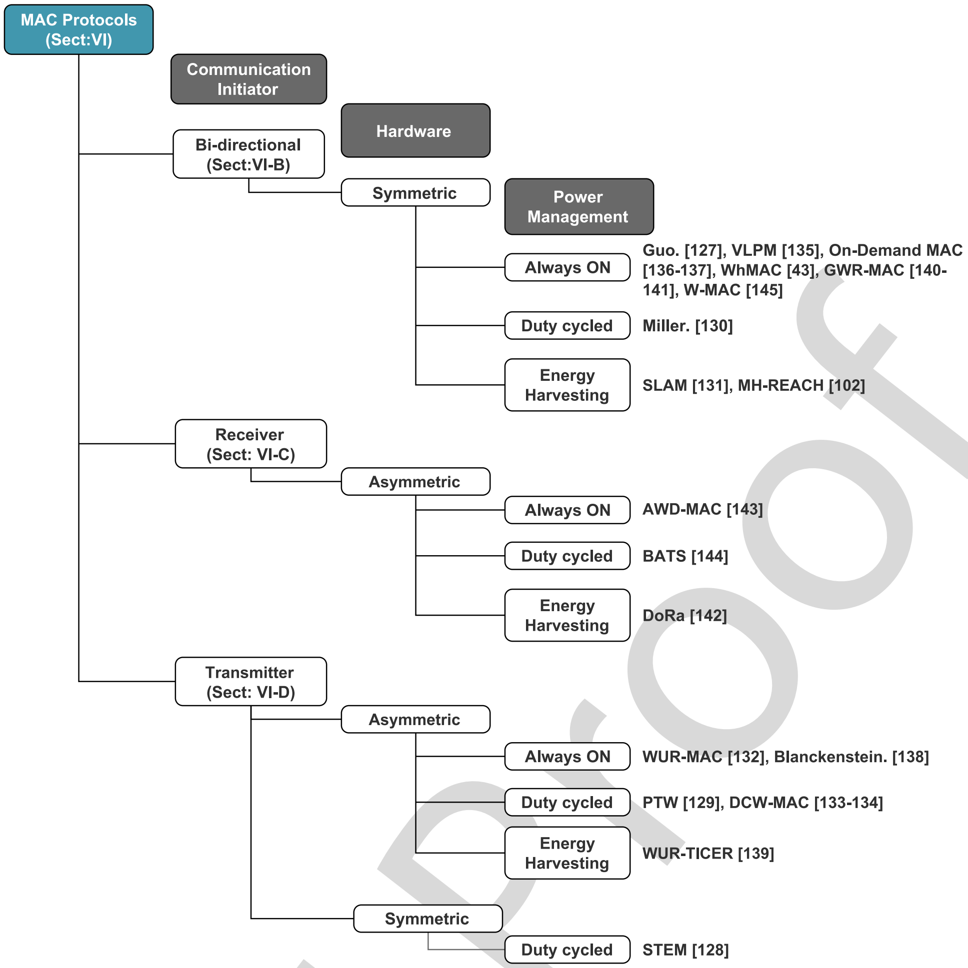


Fig. 16. Taxonomy of wake-up radio based MAC protocols.

we address properties both general to wireless medium access and specific to WuR. Table X summarizes the different WuR based MAC protocols designed so far while Fig. 16 organizes them into a taxonomy.

A. *Classification of WuR-Based Medium Access*

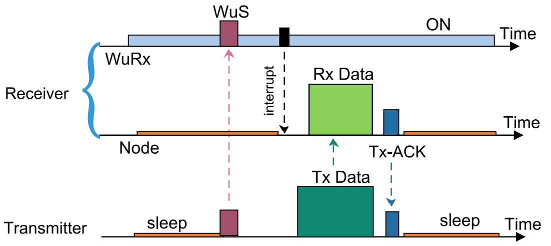
In the last decade, various MAC protocols have been proposed for wireless sensor networks. Most of these energy conservation protocols [5], [19], [23] are single-radio based and use duty cycling mechanisms. In duty cycling mode the nodes periodically wake-up to sample the channel and then go back to the sleep state. However, duty cycling MACs suffer from idle listening and waiting time that increases the data latency and power consumption (see Section I-A). Wake-up radios combat this at the hardware level, but they must also be coupled with a MAC protocol to control their use.

The main contrast between traditional asynchronous MAC protocols and MACs designed for use with WuRs is that dual-radios are utilized, one of which is the extreme low-consumption WuR. In the former, different power management techniques are applied to the main transceiver for reducing radio-on times. The latter uses different strategies to control the secondary radio while keeping the main radio off during periods of inactivity.

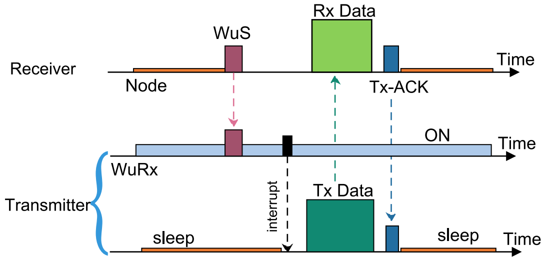
MAC protocols typically divide themselves between on-demand and scheduled, with a majority of existing WuR protocols falling into the former category for flexibility and simplicity as complex, system wide schedules are not required. Further, an on-demand approach well-suits the use of the WuR as a trigger, and avoids heavy resource requirements to build, communicate, and store schedules. Below we focus on several dimensions to on-demand communication, discussing how the WuR paradigm changes their applicability w.r.t. standard wireless communication. Fig. 17 (notably not drawn to scale) illustrates different WuR based communication schemes that can be adopted for various applications. Two channels are utilized, the WuR channel and the main radio channel. The height of the bar symbolically represents the power consumption of the respective transceivers (WuR and the main radio) in active and inactive states during different radio events while the width represents the radio on-time.

The first concern we address in the taxonomy of Fig. 16 requires identifying which pair of nodes is allocated the wireless channel based on who is the *communication initiator*: the transmitter, the receiver or either (bi-directional).

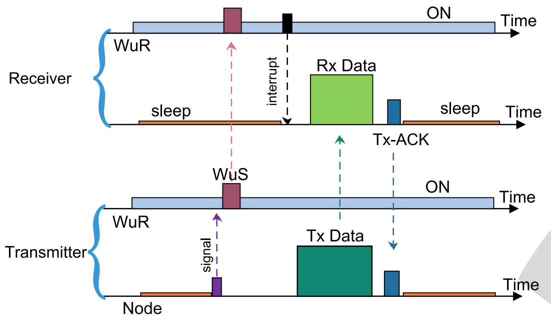
(i) *Initiator (Transmitter):* In a Transmitter-initiated protocol, the node that has data to send initiates communication (Fig. 17(a)). It first sends a wake-up



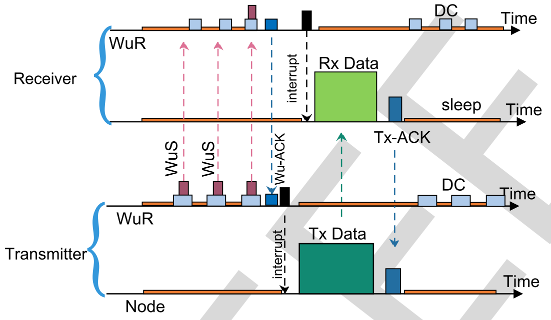
(a) Transmitter-Initiated MAC.



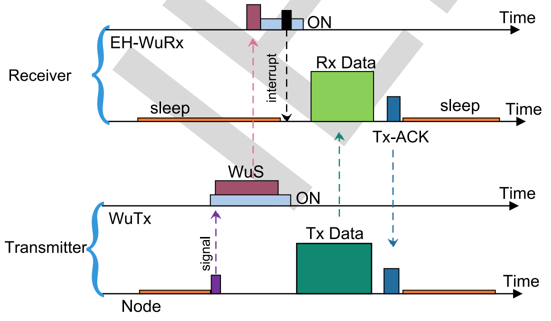
(b) Receiver-Initiated MAC.



(c) Symmetric WuR System.



(d) Duty Cycled WuR.



(e) Energy Harvesting WuR System.

Fig. 17. Various wake-up radio communication schemes.

signal, whose receipt triggers the receiver to wake up its main transceiver. Data is exchanged using the main transceivers followed by Tx-ACK if transmission was successful. The nodes then go back into sleep mode.

(ii) *Initiator (Receiver):* In Receiver-initiated systems (Fig. 17(b)), the burden of starting a communication event falls to the receiver, specifically with the node, often the sink, announcing its readiness to receive data. After this announcement, it switches to receive (RX) mode and monitors the wireless channel to receive any incoming packets. If we assume the WuRx on the sender side is always active and listening, when it receives the signal it activates its main transceiver to send the data packet. The session ends when the transmit acknowledgment (Tx-ACK) signal arrives at the sender from the destination node, after correctly receiving the data packet. All the nodes then go back to sleep mode. This communication modality is most effective when transmissions are infrequent, and collisions at the receiver are unlikely.

(iii) *Initiator (Bi-directional):* In bi-directional systems, either of the nodes that want to push or pull data can initiate the communication via their respective WuRs. The data packet is still exchanged between main transceivers. This setup is more suitable for enabling multi-hop communication.

Thus far we have ignored the placement of the specialized WuR hardware, assuming that the non-initiator is equipped with the WuRx. Here we detail asymmetric and symmetric options.

(i) *Hardware (Asymmetric):* If only a single hop network is required, an asymmetric scheme is possible, with the WuRx on only one side of the communication link. In a scenario with a powered sink, a Receiver-Initiated solution can be used to pull data to the sink from nodes that are one-hop from the sink. The non-sink nodes must have a WuRx, allowing them to wait in a very low consumption state, then switching to a higher consumption only when the sink is ready to receive their data.

(ii) *Hardware (Symmetric):* For a multi-hop system, each node must alternately serve as receiver and transmitter, resulting in a symmetric system in which all nodes are equipped with a wake-up transceiver. Either receiver- or transmitter-initiated schemes are possible. Fig. 17(c) shows a transmitter-initiated case, in which the transmitter sends a wake-up signal to the receiver. The receipt of this signal triggers the activation of the main transceivers for data exchange.

Next we turn to the usage of the wake-up radio itself, concentrating on how and when it is powered. There are three power management techniques that can be applied: always-ON, duty cycling the WuR or energy harvesting.

(i) *Power (Always-On WuR):* Typically, due to the low consumption of the WuRx technology, it can be constantly powered, waiting for a trigger signal. In a transmitter-initiated scenario, this minimizes the latency, as the receiver is immediately aware of the transmitter's need to initiate communication.

(ii) *Power (Duty Cycled WuR):* To further reduce power consumption, the wake-up radio itself can be duty cycled

(Fig. 17(d)), meaning the WuRx is periodically put into listen mode to monitor the channel for a wake-up signal. To compensate for the sleeping times of the receiver, the WuTx must send the wake-up signals more than once, until a wake-up acknowledgment (Wu-ACK) is received from the target WuRx. When the WuRx listening period coincides with the wake-up signal transmission, the receiving node switches on its main transmitter and the main data transmission is initiated. If no Wu-ACK is received, the initiator node can re-transmit the wake-up signal. To avoid overhearing by the non-targeted nodes, the wake-up signal carries the destination address.

(iii) *Power (Energy Harvesting WuR):* As mentioned in Section III, in energy harvesting WuR system (EH-WuR), the WuRx is only woken up when "sufficient" energy is harvested from the wake-up signal. Fig. 17(e) illustrates the transmitter-initiated scenario where the energy from the WuS is utilized for powering up the trigger circuitry. In this scenario when there is no communication going on, the WuRx is completely switched OFF.

We next consider two, elements that we leave out of our taxonomy, but are nevertheless considered part of the MAC. First, what information is exchanged over the WuR and second, whether the WuR works in the same frequency band as the main radio.

(i) *Data (Trigger-only):* The most typical use of the WuR is to trigger a higher power radio, used for communicating data. This requires very little logic on the WuR board, and minimizes hardware complexity. As mentioned previously, the trigger can be broadcast, waking up all neighboring nodes, or unicast, with the trigger containing the address of the intended recipient.

(ii) *Data (WuR as main data radio):* As an alternate, the low-power WuR can be responsible for all communication, i.e., for sending the wake-up signal and the data packet. The communication is still bidirectional, however, there is no main high power transceiver.

For the next option, we look at the radio itself, specifically the use of the wireless spectrum, divided into channels.

(i) *Spectrum (In-Band):* Few published MAC protocols address only in-band (single channel) communication, i.e., both the trigger and the data are exchanged over the same channel or frequency.

(ii) *Spectrum (Out-of-Band):* Multiple channels, instead, can reduce interference and increase bandwidth, but at the expense of additional coordination between senders and receivers both in time, as mentioned previously, and also across the space of the channels. In most of the WuR-MAC protocols, the bandwidth is divided into two channels: one used for control and the other for wake-up signals. Another is the data channel with higher bandwidth allocated for the main radio. For channel reservation, normally RTS/CTS handshake mechanism is performed over the control channel. The RTS/CTS frame includes a preamble, sender/receiver address, channel information for the main transceiver, and packet length. Use of out-of-band approach has following advantages. Firstly, using different channels appropriately can lead to higher throughput. Secondly, communication on different channels or frequency does not interfere with each other allowing multiple transmissions simultaneously, leading to fewer collisions.

In the remainder of this section, we organize our discussion of proposed protocols along the taxonomy of Fig. 16, first according to the communication initiator: bi-directional, receiver-initiated, and transmitter-initiated. Within each, we further sub-divide the discussion across symmetric and asymmetric hardware and different power management approaches, also offering the categorization of the protocols along the lines mentioned here.

B. Bi-Directional MAC Protocols

The most populated sector for MAC protocols is **bi-directional**, in which any node can initiate the communication. For instance, in a WBAN the traffic is normally categorized into two types: *uplink* where the sensing nodes can communicate with the coordinator node to report urgent data and the *downlink* where the coordinator can send messages to the nodes. In this framework, all the nodes can be attached with WuR transceivers providing bi-directional communication [143]. This requires **symmetric** hardware on all nodes, but affords full flexibility of **power management**, which we detail here.

1) *Always ON:* The MAC protocols in this category keep the low-power WuRx always ON. As such, it is able to receive the wake-up beacon immediately with reduced latency, however, the energy consumed is non-negligible. Several existing MAC protocols, VLPM [133] WhMAC [42], [104], On-Demand MAC [134], [135], and GWR-MAC [138], [139], have been proposed for the star topology, applying this schema using existing wakeup radios to WBAN. The authors assume that the wake-up beacon contains the target destination node address allowing other nodes in the network to keep their main radio in sleep state. However, all of these works ignore the fact that different physiological parameters sampled by different sensor nodes generally have significant differences in terms of traffic arrival and data rate. For instance, sensors monitoring electrocardiography (ECG) is allocated high data rate while body temperature sensors are assigned low data rate. If the same energy saving strategy is used to cope with all of the sensor nodes, the nodes with high energy consumption rate will quickly exhaust their energy, which eventually reduce the entire network lifetime. In addition, while some of these protocols may work well in a small, single-hop network like a WBAN, they may lack in flexibility to work for more general WSNs with a large number of nodes. Guo *et al.* [125] proposed one of the earliest protocols using always-on WuRxs to show the benefit of bi-directional over traditional radios with duty cycling MAC. The receiver assigns the nodes with unique data channels by encoding channel information in the wake-up beacon called *channel*

TABLE X
WAKE-UP RADIO BASED MAC PROTOCOL DESIGNS

No.	Protocol	Year	Initiator	Hardware	Power Management	Information Exchange	Channels	Key Novelty	Implement^{n}
1	Guo et al. [125]	2001	Bidirectional	Symmetric	Always ON	Trigger	Multiple	-Embedding channel information in WuS	Simulation
2	STEM-T [126]	2002	Transmitter	Symmetric	Duty Cycled	Trigger	Out-of-Band	-All neighbors woken up	Simulation
3	STEM-B [126]	2002	Transmitter	Symmetric	Duty Cycled	Trigger	Out-of-Band	-Addressed Beacon	Simulation
4	PTW [127]	2004	Transmitter	Asymmetric	Duty Cycled	Trigger	Out-of-Band	-Broadcast wake-up -Addressing on data channel	Simulation
5	Miller et al. [128]	2005	Bidirectional	Symmetric	Duty Cycled	Trigger	Multiple	- Wake up scheduling	Simulation
6	SLAM [129]	2007	Bidirectional	Symmetric	Energy harvesting	Trigger	Multiple	-Energy harvesting by all nodes	Simulation
7	WUR-MAC [130]	2009	Transmitter	Asymmetric	Always ON	Trigger	Out-of-Band	-CTS / RTS on WuR channel	Simulation
8	DCW-MAC [131], [132]	2011-14	Transmitter	Asymmetric	Duty Cycled	Trigger	In-Band	-Single trasmitter for trigger and data -Separate WuRxs	Simulation
9	VLPM [133]	2011	Bidirectional	Symmetric	Always ON	Trigger	Multiple	-Bidirectional wake up	Simulation
10	On-Demand MAC [134], [135]	2011	Bidirectional	Symmetric	Always ON	Trigger	Multiple	-Bidirectional wake-up	Simulation
11	Blanckenstein et al. [136]	2012	Transmitter	Asymmetric	Always ON	Trigger	In-Band	-Node clustering -TDMA on main radio	Simulation
12	WhMAC [42]	2012	Bidirectional	Symmetric	Always ON	Trigger	Multiple	-TDMA on main radio	Simulation
13	WUR-TICER [137]	2013	Transmitter	Asymmetric	Energy harvesting	Trigger	In-Band	-Energy harvesting by all nodes	Simulation
14	GWR-MAC [138], [139]	2014	Bidirectional	Symmetric	Always ON	Trigger	Multiple	-Bidirectional wake up	Simulation
15	MH-REACH [100]	2015	Bidirectional	Symmetric	Energy harvesting	Trigger	Out-of-Band	-Passive RFID	Testbed
16	DoRa [140]	2015	Receiver	Asymmetric	Energy harvesting	Trigger	Out-of-Band	-Energy harvesting -Base station wakes up the neighbors	Simulation
17	AWD-MAC [141]	2015	Receiver	Asymmetric	Always ON	Set of Triggers	In-Band	-Wake up multiple neighbors	Simulation
18	BATS [142]	2016	Receiver	Asymmetric	Duty Cycled	Trigger	Out-of-Band	-Supports Mobility	Testbed
19	W-MAC [143]	2017	Bidirectional	Symmetric	Always ON	Trigger	Out-of-Band	-Bidirectional wake-up -Addressed beacon -Supports multi-hop	Simulation

based local addressing scheme. The transmitting node captures this information via its WuRx and switches its data radio to receiver's channel after activating the main node. Through the simulation of their protocol in broadcast mode, the authors showed that power reduction of 10∼100 times can be achieved with always-on WuRxs compared to duty cycled main radio solutions. To target real WSN applications, **W-MAC** [143] was proposed for multi-hop network in which nodes alternately act as senders and receivers. W-MAC takes advantage of secondary always-on WuR that is attached to the main mote acting as the communication initiator. Whenever a node has data to send, either generated by the upper layers of the protocol stack or forwarded by neighboring nodes, W-MAC first transmits a wake-up beacon containing the destination node address. To avoid collisions, the WuR and the main radio use different channels for wake-up beacon and data packets. Using simulations with two different routing protocols, W-MAC illustrated that WuR technology has the potential to offer significant energy savings without compromising on reliability and latency.

2) *Duty cycled:* Another bi-directional communication is proposed by Miller and Vaidya [128]. To avoid costly full wake-ups, the sensor nodes schedule a triggered wake-up with a receiver. This schedule is calculated by the sink node based on the previous traffic patterns and is then disseminated to the network. Each node in the network knows their next wake-up time and when there is nothing to receive, the WuR is switched into duty cycling mode until the next wake-up cycle. The proposed idea is compared to STEM [126] and the simulations show significant reduction in the delivery latency. Nevertheless, schedule sharing requires tight synchronization at the receiver side leading to extra energy overhead to overcome clock drifts. The authors also assume that all the nodes share the same wake-up channel

without specific node addressing, thus triggering all the nodes.

3) *Energy harvesting:* **MH-REACH** is a MAC protocol designed for passive RFID-based WuR systems supporting multi-hop wake-up sensor networks [100]. In it, the WuTx on the sink wakes up all nodes in its vicinity. Any node that was woken up offloads its data to the sink, and, if it is a multi-hop node, it also transmits a wake-up signal to wake up other nodes within its transmission range. If it is an edge node, after transmitting its data to the sink, it returns to the sleep state until the next wake-up event. Although this protocol supports a multi-hop network, the passive devices require wake-up signals of longer duration (between 5s-10s) to accumulate enough energy to fully power-up the circuitry. Therefore, applications must trade-off maximum wake-up range and node lifetime. In addition, due to its broadcast nature of the WuS, all the nodes within 1-hop are activated, thus contributing to overhearing overhead. A similar energy harvesting based MAC protocol (**SLAM**) has been proposed in [129]. In SLAM, a few nodes are assigned as guard nodes that monitor the traffic between hops to detect malicious nodes. During periods of inactivity the guard nodes are put into sleep mode and switched on when required via passive WuRxs. Through experiments authors have shown that listening energy can be reduced by to 30-129 times using WuRs while providing a high level of network security.

C. Receiver-Initiated MAC Protocols

To increase throughput and to shift the burden of energy consumption from the sender to receiver, some authors have proposed **receiver-initiated** WuR-MAC protocols. Their design is inherently **asymmetric**, and the full range of power management techniques are applicable.

1) *Always ON:* To extend the life of sensing nodes, **AWD-MAC** [141] utilizes the receiver-initiated scheme but employs a single channel for communication. Different from the traditional receiver-initiated cycled receiver (RICER) where only one common broadcast beacon is sent, AWD-MAC first sends a set of wake-up beacons in sequence to wake-up multiple neighbors for neighbor discovery. The nodes then reply using random slots with their node IDs and respective data rates. Subsequently, the coordinator node creates a neighbor table to query each node in an asynchronous fashion. AWD-MAC claims that the collisions are removed as only one transmitter node is allowed to send its data at a given time while sharing the same channel. Nonetheless, collisions do occur during the neighbor discovery phase when AWD-MAC sends the broadcast beacon to detect new nodes.

2) *Duty cycled:* The first mobility-based WuRx system using the receiver-initiated paradigm has been proposed in the **BATS** project [144]. The authors have investigated the potential of ultra-low power WuRs carried by bats to monitor encounters between individuals and to track their routes at high spatial and temporal resolution [142], [145], [146]. Due to limited available energy, the wake-up receivers are duty cycled. To support multiple mobile nodes and to prevent the collisions at the receiver side, the ground node uses Time Division Multiple Access (TDMA)-like communication slots with guard intervals between slots. The communication between the mobile nodes is not synchronized. When the mobile node enters the communication range of the ground node, the latter sends a wake-up beacon. Upon successful wakeup, the mobile node offloads the data within its assigned slot. Due to the high mobility of the bat nodes, no carrier sensing techniques are performed prior to transmission allowing mobile nodes to send data before exiting the transmission range. Therefore, if multiple mobile nodes are within the receivers vicinity, data collisions may occur and the packets can be lost.

3) *Energy harvesting:* **DoRa** [140] offers a WuR-MAC protocol that builds upon the foundation of the receiver-initiated paradigm for the realization of energy harvesting in one hop networks. In the proposed mechanism, no channel reservation or packet acknowledgments are transmitted. The nodes answer to the base station by directly sending the data packet. DoRa also provides out-of-band support and node addressing. However, similar to MH-REACH, a strong wake-up signal is required in order to harvest enough energy to activate the nodes leading to high data latency.

D. Transmitter-Initiated MAC Protocols

We next consider **transmitter-initiated** MAC protocols where each node chooses its transmission schedule autonomously. In general, this approach puts the energy consumption burden for transmission on the sender, with a much lighter load on the receiver. Both **asymmetric** and **symmetric** approaches are possible, and multiple power management techniques have been applied.

We begin with **asymmetric**:

1) *Always ON:* A transmitter-initiated MAC protocol leveraging always-on WuRxs is proposed by Mahlknecht and Durante [130]. WUR-MAC is based on multi-channel principle and uses RTS and CTS handshake mechanism. The sender node first transmits the request-to-send packet for selecting the appropriate receiver. The intended node then replies with clear-to-send packet and triggers its main radio for data reception at higher bandwidth. WUR-MAC supports both point-to-point and broadcast communication. Using channel reservation reduces collisions but may impact on the data latency as the transmission is blocked until CTS is successfully exchanged. Energy efficient node clustering using WuRxs for WBAN sensors with similar readings is presented in [136]. To eliminate idle listening and channel contention, an always-on WuRx is attached to a main radio that utilizes TDMA scheme. To achieve clustering, the relevant data information is

encoded in the WuTx's data pattern. The idea is to reduce energy consumption by reducing the number of data packets through clustering nodes with similar sensor readings and allowing only the cluster head to forward data to the sink. This protocol is only tested using simulations where the wake-up addressing mechanism is used to trigger nodes according to the data they have sensed.

2) *Duty cycled:* Similar to STEM-T, Yang and Vaidya [127] propose a Pipelined Tone Wakeup (**PTW**) scheme that uses two different radio channels, one for data and one for tone detection. In PTW, the WuRx is duty cycled. When a node has packets to send, it transmits a tone on the wakeup channel and sends the notification packet on the data channel to specify the target node. As the wake-up tone is broadcast, any node within the transmission range of sender will be awakened. From the point of view of application scenarios for opportunistic networking, such an approach could grant fast wake-up in dense and multi-hop scenarios while reducing end-to-end latency, but could be less energy efficient. Analogous to STEM and PTW, the work in [131] and [132] also duty cycles the WuRx statically, but uses in-band approach for communication. In **DCW-MAC**, the main radio is used for both sending the wake-up beacon and the data, but the authors add dedicated, secondary low-power radio, acting as a WuRx, operating in the same frequency band. The authors through analytical models derive the optimal sleep and listen time for a duty cycled WuRx and compare these models to a non-WuR based system. However, the analysis assumes perfect detection of wake-up signals and energy consumed due to collisions is ignored in the derivation of optimal timing. In addition, the main radio also acts as a wake-up transmitter, hence, frequent switching between RX and TX mode may result in extra energy consumption.

3) *Energy harvesting:* Le *et al.* [137] have proposed the **WUR-TICER** MAC protocol that operates by harvesting energy from the ambient environment. The protocol is based on nano-watt WuRx proposed in [147] embedded with an energy harvesting WSN node. Whenever the transmitter has a packet, it broadcasts a wake-up beacon (WUB) indicating to other receivers that it is ready to send. Since the main radio has been used as a WuTx, WUR-TICER utilizes the same channel for sending the WUB and the data packet. As a result, WUR-TICER achieves a lower packet reception rate than the non-WuR model since the WUB collisions are frequent when two or more transmitter nodes wake-up at the same time and try to send a WUB to the base station. Moreover, the WuR is only simulated in a single-hop energy harvesting WSN with a continuous energy source.

Moving on to **symmetric** protocols, we find only one:

1) *Duty cycled:* **STEM** [126] is one of the first transmitter-initiated protocols that separates the data transmission channel from the wake-up channel by using a dual radio approach on separate frequency bands. Both the radios are high power radios while one of them acts as a WuR. Two variants exist in STEM. In STEM-T, a tone is sent which wakes up all the nodes in the neighborhood. STEM-T resembles the traditional preamble sampling approach but moves the data transmission to a separate channel. In STEM-B, a wake-up beacon is used as a preamble that includes the address of the destination node and the sender. A node thus can determine whether it is the intended receiver or not and the non-target nodes can go back to sleep earlier. Moreover, STEM uses a regular high power radio as a WuR to achieve the same coverage as the main radio. Duty cycling is applied to the WuR while the data radio is switched off unless required. However, both radios are high power radios and the power consumption is not reduced.

E. Summary

To make the wake-up radio based system feasible and energy-efficient, it requires careful design of energy-efficient protocols. The MAC layer plays a crucial role in coordinating how nodes share the common broadcast channel. The main role of this layer is to prevent simultaneous transmissions and data packet collisions at the same time granting energy efficiency, low channel access delays and ensuring fairness among the nodes in the network.

So far various asynchronous MAC protocols have been proposed for WuRs to extend the network lifetime and to increase reliability and throughput. Within this, different communication and power management techniques have been employed. For reducing latency, active WuR based MAC protocols have been proposed. This allows fast response and long communication as the radios are always on. Although this technique provides many advantages, it is less energy efficient as WuRs are always on and dissipate energy. To make this approach effective, energy-efficient WuR hardware design is required. Some works have proposed energy harvesting based MACs and use energy from the wake-up signal itself. The reason is to extend the node lifetime and to only turn on the device upon detection of the valid signal. Other sets of protocols have duty cycled the WuRs. Although this reduces power demand but encounters same problems as traditional MACs such as increased latency.

To enable on-demand communication, asynchronous WuR-MAC protocols have mostly adopted transmitter initiated probing for data transmission. The nodes are only equipped with the WuRxs (asymmetric) while the main radio is utilized as the transmitter. This allows only one-way communication and does not exploit the full potential of WuRs. For the WuR based system to be effective and applicable for various applications bi-directional MACs are more suitable. The main radio-activity is reduced by exchanging control information over the WuRs. This information can include channel or frequency reservation data, which otherwise would have been exchanged over the main radio.

As the number of WuR-MAC protocols grows, there are still many open questions such as the different performance they offer when applied to realistic applications. Most of the protocol evaluation concentrates primarily on simulation results and does not include any results from hardware implementations or testbeds. Moreover, their implementation relies on custom-design software limiting the reproducibility of the obtained results. Some of these works have quantified the benefits of using WuRs in terms of energy consumption through in-lab power measurements, but do not evaluate other relevant metrics, such as latency and end-to-end data reliability. While some of these protocols may work well in a small, single-hop network like a WBAN, it may lack in flexibility to work for more general WSNs with a large number of nodes.

VII. ROUTING PROTOCOLS UTILIZING WURS

In typical WSNs, hundreds or thousands of sensor nodes are scattered or placed throughout a large area. Each sensor has the capability to communicate, collect, and route data to other nodes or back to the base station. Since, not all of these sensors are in range of the base station, data is routed in a multi-hop fashion. Over the last several decades, a plethora of routing strategies have been proposed for WSNs [25]–[28]. However, most of these studies are based on single radio architecture. The scenario changes when routing is done over WuRs due to the network topology induced by it.

One of the challenges of introducing a WuR as a new component to an existing node with wireless communication is the mismatch between the ranges. By nature, WuR technology has shorter ranges, prohibiting a wake-up signal from triggering a distant node, despite the ability of the higher power radio to effectively reach it. This introduces new challenges for traditional routing protocols. In particular, for WuR based systems, packets need to be routed through longer paths than those of the main radio. This affects the data latency as well as the network lifetime. For applications with stringent consumption requirements, this may not be acceptable. To mitigate this, several WuR based routing protocols have been developed for flooding, multi-hop data collection and dissemination. Table XI summarizes the WuR-based routing protocols that we survey while Fig. 18 arranges them in a taxonomy based on whether they address only the routing layer or are also cross-layer.

A. Routing-Only Protocols

Existing routing-only protocols exploiting wake-up radios can be classified into three categories: topology-based, load balancing, or tree-based.

1) Topology Based: Under this category, every node in the network maintains routing information such as its end-to-end distance to the sink and also the next hop to reach the sink. This information is usually obtained by the sink using a network wide dissemination of control messages. To forward a packet towards the sink, the node chooses the neighbor that has the shortest path as the next forwarder.

Stathopoulos *et al.* [148] present a topology control mechanism for establishing the end-to-end paths in a WSN using the dual-radio system. Each node uses its low bandwidth wake-up radio to request an end-to-end path information to the destination nodes from the central *topology controller*. The novelty of this work is to use multiple short WuR hops to achieve a single, long higher power hop by the main radio. This protocol is based on an out-of-band paradigm and supports multi-hop networks. Latency is the main issue here as path discovery using low data rate networks can be time-consuming. Since the topology controller is centralized, this can lead to a single point of failure, crippling the entire network.

The concept of semantic addressing using WuRs, in which a pool of multiple WuRx addresses is assigned to a node and dynamically updated based on its status, has been recently proposed [39]. A dedicated WuRx-enabled communication stack called **FLOOD-WUP** exploiting selective wake-ups and dynamic address assignment is implemented to enhance system performance. FLOOD-WUP enables transmission of commands from the sink to the sensor nodes in a reliable and energy efficient way. Comparing FLOOD-WUP against traditional flooding protocol has shown that nodes using FLOOD-WUP for interest dissemination are 4% energy efficient and require less energy to achieve full network coverage.

2) Load Balancing: Routing protocols designed for load balancing not only select the shortest paths towards the destination but can also consider the available energy of the nodes in the path in an attempt to extend network lifetime. The routing load is distributed over multiple paths in the network to improve packet latency and to minimize dropping packets.

To achieve reliable end-to-end data delivery, a load-balancing, and optimized data flow communication routing tree is proposed by Vodel *et al.* [149]. **WRTA** is a lightweight routing protocol for data-centric WSN environments that combines complex route path calculations and topology optimization mechanisms for asynchronous communications. In WRTA, the burden of energy consuming calculations such as maintaining routing path and network status is shifted from the sensing nodes to the sink. For load-balancing and route optimization, the shortest path is selected for nodes with a large amount of data depending on the energy level, QoS parameters and bandwidth of the nodes. WRTA was analyzed using both software and hardware experiments. It was observed that for a network with the depth of 3-hops, the proposed routing protocol experiences high packet loss when the number of packet generation increases to 7 packets per node/min.

3) Tree-Based: In tree-based routing, nodes form a tree-like hierarchy with the sink node as the root. Each node (child) at the particular depth of the tree transmits data to a node (parent) in the upper level of the hierarchy. This ensures data transmission in parallel and reduces packet latency significantly.

Recently, Gnawali *et al.* [150] extended the Collection Tree Protocol (CTP), the *de facto* standard for data collection in WSN to work with nodes coupled with WuRs [151]. **CTP-WUR** utilizes WuRs to relay wake-up requests and reduces end-to-end data latency, thereby, extending the achievable wake-up range. CTP-WUR can handle both broadcast and unicast packets. It has been shown through simulations that CTP-WUR performs better, obtaining latencies lower than tens of microseconds and is highly reliable compared to the standard CTP.

TABLE XI
WAKE-UP RADIO BASED ROUTING PROTOCOLS

No.	Protocol	Year	Path Request	Hardware	Addressing	Topology	Implementation
1	EAR [152]	2002	Source	Symmetric	ID-based	Distributed	Simulation
2	LESOP [153]	2007	Source	Symmetric	ID-based	Distributed	Simulation
3	Stathopoulos et al. [148]	2007	Source	Symmetric	ID-based	Centralized	Testbed
4	WRTA [149]	2012	Sink	Symmetric	ID-Based	Centralized	Testbed
5	FLOOD-WUP [39]	2014	Sink	Symmetric	ID-Based	Distributed	Simulation
6	CL-RW [154]	2014	Source	Symmetric	ID-Based	Distributed	Testbed
7	ALBA-WUR [54]	2015	Source	Symmetric	ID-Based	Distributed	Simulation
8	ZIPPY [37]	2015	Sink	Symmetric	ID-Based	Distributed	Testbed
9	CTP-WUR [151]	2016	Source	Symmetric	ID-Based	Distributed	Simulation
10	OPWUM [155]	2016	Sink	Symmetric	ID-Based	Distributed	Simulation
11	T-ROME [156]	2017	Source	Symmetric	ID-Based	Distributed	Testbed

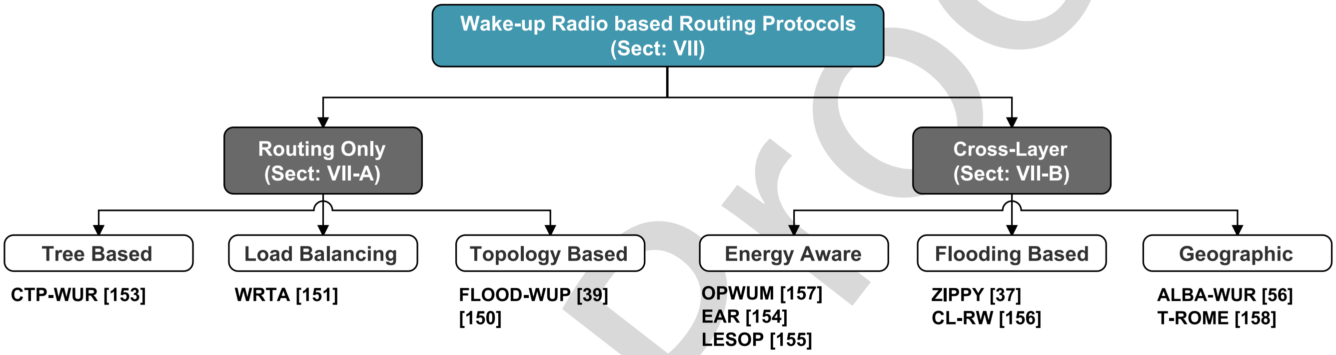


Fig. 18. Taxonomy of wake-up radio based routing protocols.

B. *Cross-Layer Protocols*

The protocols discussed so far were individually developed for a single layer of the stack, i.e., MAC, Network, Transport, and Physical. While they exhibit good performance in terms of the metrics related to a single layer, they are not jointly optimized to maximize overall network performance while reducing energy expenditure. Therefore, a cross-layer design presents a promising alternative by streamlining communication between layers and providing the response based on a complete view of the stack, increasing system utility and energy efficiency.

1) Energy-Aware: The main objective of energy-aware routing protocols is to extend the network lifetime by choosing optimal paths. These paths are chosen depending on the energy budget so that no single path depletes its energy quickly. Rotating among paths leads to increased network lifetime as energy is dissipated equally among all the nodes.

A cross-layer energy aware routing (**EAR**) protocol using WuRs [152] uses sub-optimal paths to provide substantial gains in network lifetime. In EAR, the MAC layer is responsible for keeping the lists of all its neighbors and metrics such as the neighbor's position and the energy required to reach it. Then, this list is accessed by the network layer to make decisions regarding packet routing. The energy level information is used as a weight factor when routing the data, avoiding the paths with less residual energy. Finally, to send data the MAC layer transmits a wake-up signal on the broadcast channel, modulating the address of targeted node with the wake-up signal. Even though this method takes energy into account, it does not consider end-to-end latency. Moreover, this protocol has only been evaluated through simulations.

OPWUM [155] offers another opportunistic cross-layer MAC protocol leveraging WuRxs for selecting the best receiver among its neighboring nodes using energy as a metric. To overcome collisions between wake-up beacons, a clear channel assessment (CCA) is performed using the WuTx. Thereafter, an RTS-CTS is exchanged between the WuTx and WuRx before sending any data packets via the main radio. One of the features of OPWUM is that all the next hop relay selection phase is carried out using wake-up beacons only. Nonetheless, this proposed protocol has not been tested using real experiments.

Unlike classical approaches, Low Energy Self-Organizing Protocol (**LESOP**) [153] presents a cross-layer architecture where both Application and MAC layers collaborate directly while Transport and Network layers are excluded to simplify the protocol stack. Inter-node communications are done by exchanging packets and busy tones. The main radio is responsible for handling all data packets while the busy tones are sent using the secondary low power wake-up radios. This protocol is proposed for target tracking applications in large wireless sensor networks. Similar to EAR, this protocol does not investigate the importance of system delay and is tested in simulations only.

2) Geographic: In geographic routing protocols, the data packet is routed towards the destination region using geographically informed neighbor selection heuristics. The key concept is to collect data from the selected region rather than sending it through the whole network hop by hop.

Spenza *et al.* [54] proposed **ALBA-WUR**, a cross-layer solution for data collection exploiting semantic node addressing features of WuRx to implement complex relay selection policies. For data routing and path selection, the protocol relies on ALBA-R, a cross-layer geographic protocol that features the integration of awake/sleep schedules, MAC, routing, load balancing, and back-to-back packet transmissions [157]. Simulation results concerning average end-to-end data latency show that the use of WuR technology together with ALBA-R is effective for cutting down the time needed to deliver packets to the destination. However, this delay is dependent on the data rate used to transmit wake-up signals.

T-ROME, a cross-layer routing protocol that supports multi-hop communication, is presented in [156]. At the MAC layer, T-ROME uses RTS/CTS messages to reduce packet collisions over the WuR. At the network layer, the data forwarding mechanism of T-ROME is similar to ALBA-WUR but does not flood the whole network. In T-ROME the next hop node is chosen dynamically using link quality estimation over the WuRs to determine if the relay node is within the wake-up range. If so, the data is directly sent to that particular node without passing from each child to its parent. Therefore, T-ROME saves energy by skipping nodes during data transmission. Using small scale testbed, authors have shown that T-ROME outperforms CTP-WUR in terms of number of hops required to reach the sink with reduced latency and power consumption.

3) Flooding Based: In this category, the node that has data communicates it to everyone else in the network using flooding. Multiple copies of the incoming packets are sent by the nodes that are in the broadcast domain which they forward to their neighbors. This technique generates a huge amount of redundant traffic. However, it does not require costly topology maintenance and route discovery procedures.

A practical application of ultra-low power sub-GHz WuR is presented by Sutton *et al.* [37]. **ZIPPY** is a cross-layer protocol that provides on-demand network flooding for the multi-hop network through the use of ultra-low power wake-up receivers equipped at each node, albeit with reduced per-hop range compared to using high-power transceivers. The ZIPPY protocol features asynchronous network wake-up, neighborhood time synchronization, bit-level data dissemination and carrier frequency randomization leveraging low complexity WuRs. Using ZIPPY reduces the entire network flooding time while maintaining end-to-end latency of only a few microseconds. As in its current implementation, ZIPPY does not address the false wake-ups making it susceptible to erroneous network wide wake-up.

Cross-layer Radio Wake (**CL-RW**) [154] builds on the transmitter-initiated paradigm by coordinating the wake-up beacon transmissions. The proposed mechanism uses an asynchronous scheduler for controlling its WuR, which is a cross-layer information from the MAC layer, to form an operation cycle. This cycle is a network-level duty cycle that is built on top of the duty cycles of individual nodes. Instead of transmitting wake-up beacons independently, each WuTx transmits during its allocated schedule. Therefore, the beacon transmissions in a network are coordinated to form a multi-hop path like a pipeline and the waiting time in each hop is significantly reduced. Furthermore, a node that has generated data can keep the radio off to save additional power. The proposed idea is compared to AS3-MAC [158] and the experiments show significant reduction in the power consumption.

C. Summary

This section has provided a classification of WuR based routing protocols, including also cross-layer approaches. Most of these studies have shown that by combining wake-up capabilities with selective addressing and routing over WuRs, node lifetimes can be extended to decades while achieving data latencies comparable to networks that only use the single main radio.

Most of the routing protocols discussed in this section assume static networks where the sensor nodes and the base station are stationary. An interesting issue to look into will be consideration of node mobility. For diverse applications of WuRs such as smart city or transportation, routing protocols for mobile WSNs will be beneficial to provide real-time delivery and wider coverage. Routing messages in a mobile scenario is challenging since route stability becomes an important optimization factor, in addition to bandwidth and energy. Use of wake-up radios for mobility purposes requires optimization of transmitter operation, such as the number and time interval over which to transmit wake-up beacons so that they are correctly received by the low power wake-up receiver for controlling main radio operation as proposed in [159]. Novel routing algorithms are needed to handle the overhead of mobility and topology changes in such an energy-constrained environment.

Multichannel routing protocols have recently gained popularity in the context of WSNs, due to their ability to be resilient against interference and collision, providing a significant performance benefit over a purely static approach. Such protocols involve various challenges such as channel selection, hidden terminal problem, and channel hand-over. Thus, routing for multi-channel WSNs over wake-up radios needs to be further studied.

Network security is another aspect that needs to be considered. Routing protocols must be robust against eavesdropping and malicious behavior. An attempt to address this using wake-up radios has been made in [160].

Finally, most of the routing protocols that exploit wake-up radios for the WSNs have been evaluated principally through simulations. To assess the real benefit and the performance of these protocols, thorough testing in real environments with a large network is essential.

VIII. KEY APPLICATION AREAS

Over the decades, the application of WSN has increased, spanning from monitoring natural phenomena such as

TABLE XII
WAKE-UP RADIO BASED APPLICATION REQUIREMENTS

Applications	Range	Lifetime	Mode of Data Collection	Network Type	Latency	Data Rate	Addressing	Power Source
WBAN Implantable devices	- -	++	Event-driven On-demand	Star/Single-hop	- -	++	Yes	Active
Smart City Infrastructure monitoring Environment monitoring	++	+	Event-driven On-demand	Node-to-node Multi-hop Mobile	-	+	Yes	Active Passive
Smart Metering Utility monitoring	+	+	On-demand	Node-to-node Mobile	-	+	Yes	Active
Wildlife Monitoring Contact detection	++	+	Event-driven Periodic	Node-to-node Multi-hop Mobile	-	-	Yes	Active
Surveillance	++	++	Event-driven	Star Multi-hop	- -	++	Yes	Active
Indoor Localization	+	++	Event-driven On-demand	Star Multi-hop Mobile	- -	++	Yes	Active
Asset Tracking	+	++	Event-driven On-demand Periodic	Star Multi-hop Mobile	+	-	Yes	Active Passive
Wearables	–	++	Event-driven On-demand	Star Node-to-node	- -	++	Yes	Active
Smart Grid	+	++	Event-driven On-demand	Star Multi-hop	- -	+	Yes	Active Passive
Requirement Importance	- Low	- - Very low	+ High	++ Very high				

temperature and humidity to personal health. With the proliferation of low power and cheap semiconductors, WSNs are expected to gain even more popularity [2].

With the understanding of the ultra-low power WuR built in the previous sections, we now briefly discuss multiple emerging application scenarios that can take advantage of it. We then map the different prototypes and protocols suitable for each application. Table XII offers an overview while the remainder of this section provides details.

A. Wireless Body Area Network (WBAN)

Wireless body are networks (WBANs), find applicability in medical applications and thus require high reliability. To support a variety of applications on or inside the body, systems must have low power consumption and support variable data rates [161]. As an example of the latter, a glucose level monitor requires less than 1 kbps while an ECG can reach 192 kbps [161]. Further, WBAN communication can be periodic, event-driven, e.g., triggered by detection of an alert condition, or on-demand, e.g., in response to an external request by a clinician to retrieve saved data.

WuR technology can be applied in two principle ways. First, it can be used as a trigger to initiate high data rate communication. Alternately, it can be used as a low rate, low consumption data radio [162]. Notably, the short range is not an issue for these applications [163], and the extremely low standby consumption is a major advantage. For example, a receiver sensitivity of -40 dBm is sufficient to receive a signal transmitted with 0 dBm [164]. With low sensitivity demand, energy efficient WuRs can be implemented as a simple star topology with the number of nodes typically ranging from two to ten.

1) Matching Prototypes: From the list of prototypes in Table VIII, there are 23 WuR designs that match the criteria for the first scenario. All of these designs are ultra-low-power consuming, below 10 μW, and have node addressing capabilities. For the second scenario where WuRs can be used as a full data transceiver, five concepts [36], [66], [72], [73], [99] are found to be suitable. Four out of five of these are tested prototypes while the design concept by Jean-François *et al.* [73] is only in simulation. Nevertheless, all of them have data rate above 200 kbps while exhibiting power demand below 10 μW.

2) Suitable Protocols: From the system design perspective, there are a few WuR enabled MAC protocols specifically designed for BAN applications. To offer high data rate and low latency, all of these are always-on wake-up MACs. The protocol proposed in [136] is transmitter-initiated while AWD-MAC [141] is receiver-initiated. However, we argue that the MAC protocols suitable for WBAN should be bi-directional so that anomaly can be reported effectively and on-demand. Protocols such as those presented in [42], [133], [134], and [138] are best suited for this. For communicating data, WBAN applications require either star or single-hop network, therefore, the complex routing protocol is not essential.

B. Smart City

The concept of the Smart City is growing in popularity as sensors placed throughout cities are used to support both the public administration as well as citizens directly. A large number of the placed sensors exploit wireless communication and are battery powered, allowing them to be opportunistically placed. Nevertheless, this necessitates low power operation.

Today, a majority of smart city nodes communicate wirelessly over a variety of links such as IEEE802.15.4, IEEE802.15.4g, IEEE802.15.1 (Bluetooth), or low-power 802.11 [165]. WuRs can play a critical role in making these networks more energy-efficient, scalable, and autonomous. For example, a single-hop case can be built in which a mobile data collector, e.g., a bus or garbage truck, is equipped with a WuR. This mobile data collector traverses the city and collects information from WuR based sensing nodes deployed along its route. The sensing nodes will only be activated when the mobile data collector sends the WuS querying these nodes for data (on-demand) [17]. The feasibility of utilizing WuRs for data aggregation and for opportunistic networking in a smart city scenario has been demonstrated in [166].

Infrastructure monitoring is also possible by using WuRs in a multi-hop manner [167]. A stationary or mobile data collector can gather data from a chain of sensors attached to a bridge, tunnel or simply along the streets. WuR enables the higher power sensing nodes to remain in low energy mode when there is no data to send. Instantiating this scenario, however, necessitates a solution for the mismatch between the typical distance of the WuR and that of the primary radio.

1) Matching Prototypes: In order for the WuR to be suitable for smart city applications, it should support reasonable data rate, long communication range for wider coverage and low power operation. We have identified four prototypes that meet these specifications [36], [40], [54], [67], i.e., prototype numbers 15, 21, 41 and 67 listed in Table VIII. Most of the prototypes in Table VIII do not meet this criterion since either power consumption is high, a factor that limits node lifetime if battery powered or has shorter communication range than 40 m. Non-RF WuRs are not suitable due to the requirements imposed by the hardware such as sensitivity and LOS for optical based systems.

2) Suitable Protocols: The sensors deployed within the smart city may either report periodic or on-demand data with various traffic loads. This adds an additional reliability criterion in addition to coverage and responsiveness. For instance, infrastructure monitoring systems demand fast responsiveness and should be energy efficient. That is, the events should be rapidly detected and reliably communicated in an energy efficient way through a multi-hop network for post-processing. Thus, the protocol should support event-triggered as well as periodic sensing. Various flavors of the surveyed MAC protocols can be adopted. For low latency, broadcast based MAC protocols such as PTW, AWD-MAC, and STEM-B are suitable candidates. Sensors that may rely on energy harvesting technologies can utilize SLAM, WUR-TICER, and DoRa as main MAC. If a specific node is to be queried bi-directional MACs such as W-MAC are applicable. For periodic sensing where nodes can be switched off during periods of inactivity, duty-cycle wake-up MAC should be considered.

After a certain duration, nodes may fail due to battery depletion or other external factors, therefore, new routes have to be established. Thus, the routing protocols should be adaptive and provide support for multi-hop data collection. For rapid data dissemination, network flooding protocols such as ZIPPY and FLOOD-WUP should be adopted.

C. Smart Metering

Smart meters enable remote, wireless reading of current meter values, eliminating the need for a technician to enter the home. Typical installations today place a mains powered, wireless communication unit on the meter and a mobile unit carried by a technician in a mobile vehicle. While this saves the time and energy of the technician to visit each meter, the radio itself must be powered to wait for the reading signal.

Instead, a utility meter equipped with a WuRx [168] can be activated on-demand, requiring zero or near-zero consumption in between readings. To be acceptable, the solution must have ultra-low consumption (10+ years battery lifetime at 1 reading per month). Since utility meters are usually placed inside the building, it should also have good radio signal penetration and high sensitivity operating in a sub-GHz frequency. Typically a communication distance of 15 m is required. According to communication standards for smart metering in Europe [169], the maximum allowed effective radiated power (ERP) in 868 MHz band is 25 dBm. A receiver with a minimum sensitivity of -75 dBm will be able to receive packets at a distance of 15 m. The required data rate for smart metering applications is moderate, supporting data rates between 2.4 kbps and 200 kbps. Moreover, the WuR should have addressing ability in order to query specific smart meter with its unique serial number.

1) Matching Prototypes: From Table VIII, eight prototypes match the requirements imposed by smart metering application. The designs presented in [36], [37], [40], [54], [56], [61], [62], and [67] exhibit power consumption below 60 μW with good receiver sensitivity and node addressing capabilities while offering tens to hundreds of kbps data rate.

2) Suitable Protocols: Usually, the communication will be infrequent and demand-driven, i.e., upon a request from the data collector, therefore, polling based (taking-turns) MAC protocols best suits smart metering applications. With regard to routing, various WSN protocols may be considered [170]. However, mostly WuR-enabled meters will communicate to the collector in one-hop, then complex routing protocols are not suitable but require to maintain end-to-end reliability with nodes to be uniquely identified.

D. Wildlife Monitoring

Use of sensor networks for wildlife monitoring has gained momentum in the recent years. Wildlife monitoring is essential for keeping track of endangered wild animal movement patterns, habitat utilization, population demographics, snaring and poaching incidents and breakouts. For example, WildScope [171] project attaches sensor nodes on wild animals like deer and foxes to track and to study their interaction and feeding behavior.

Data collection from wildlife has been one of the hindrances in the past, thanks to sensor equipped animal collars it is much easier and cheaper now. These collars have various integrated technologies like GSM and GPS module for tracking, high power transceivers with long range for animal proximity detection and wireless data off-loading. Due to continuous mobility, the collars require battery power with lifetime extending from few weeks to months.

To prolong the lifetime, animal collars mostly use duty cycling MACs such as low power listening (LPL), where the nodes periodically wake-up, transmit the data and then go back to the sleep state. Normally, low sampling intervals ranging between an hour and a day is chosen, since a higher sampling rate would deplete batteries too quickly. However due to the periodic operation, if there are any events of interest such as interactions between animals during this inactive period of the sensor node, it will be missed and not detected at all.

The problems mentioned above motivates the use of WuR technique for lifetime extension in wildlife monitoring scenarios. Similar to health-care, the benefit of WuR for wildlife monitoring purposes can be two-fold: either it can be used as a *"contact sensor"* or as an *initiator* for data communication. For example, collars designed in WildScope [171] project use high power CC2420 radio to listen to the beacon channel for a length of time and captures the ID number of the nodes within its proximity. This method for contact detection is expensive in terms of high idle listening power consumption. Instead, WuRs can be used as a "contact sensor" while sniffing the channel for detecting other WuRs in proximity. In this manner, all the proximity beacons between animals can be captured in an energy efficient way. Not only it will reduce power consumption, but it will also reduce the latency of contact detection due to always on feature of WuR. One such example can be found in [146] where researchers have utilized WuRs to monitor contacts and encounters between individual bats.

As a communication initiator, WuRs can be used to trigger nodes in a multi-hop network for offloading data to the base station, where a logical connectivity map can be constructed. Researchers can put data collectors equipped with WuR plus data transceiver and large energy supply near places where animals are expected to aggregate such as water source or ponds. When the animals are within the range of the data collector, the radio on them will be triggered by the WuR. Then the collars can start transmitting the gathered sensor data via the main data transceiver to the data collector. Hence, the collars may last for years and the battery replacement and retrieval cost can be saved.

1) Matching Prototypes: The salient criteria for WuRs for wildlife applications is that it should be low cost, power efficient and communication range (>30 m) that allows the network to cover a much larger area with few devices. The prototypes that match smart city applications are also suitable here but do not demand high data rates. Nevertheless, the performance of radios in terms of communication range may degrade when moved to environments with varying vegetation, thus radios with high sensitivity plays a key role.

2) Suitable Protocols: As far as MAC protocols are concerned, it should support both event-driven mode for applications like contact sensing as well as the periodic mode for data off-loading. Thus, adaptive MAC approach is required where during inactivity, the collars can save energy by duty cycling the WuRs and during encounters with other collars it can switch to continues listening mode. The MAC protocol should be able to dynamically adapt taking into account the collar activity.

In wildlife applications data is usually collected in delay-tolerant manner where it is stored locally and forwarded to the gateway when encountered with the mobile or fixed collector nodes. Low volume data can be forwarded using proactive routing algorithms that use shortest path such as EAR [152] or CTP-WUR [151].

E. Security and Surveillance Systems

Traditional security systems are based on high power central cameras that process and generate alarms if unauthorized objects or personnel are detected within the premises. Such systems are power hungry due to heavy image processing algorithms and require installation near the stationary power source. For applications such as continuous monitoring of large and wide area facilities, i.e., power plants, border lines, large factories, gas and oil pipelines with no stationary power source, infrastructure for cabling can, therefore, be very expensive.

WuRs with small, low cost and low power camera systems can thus be used to detect unauthorized objects, beyond the perimeter of some critical infrastructure. The monitoring area can be covered with several WuR based camera systems, working independently and stationary. All these units will be wirelessly connected to the main system for decision making. Once an intrusion is detected via wake-up cameras, the more powerful camera system can be triggered for verification and security action. To further reduce the camera activities, low power sensors with WuRs can be added as a separate network tier. The benefits for multi-modal sensing has been proposed in [172] and its extension with WuR is presented in [15]. The authors have presented a two-tier WSN for video surveillance applications where the communication between the PIR sensor nodes and the camera nodes is performed over the wake-up receivers.

1) Matching Prototypes: The coverage and the response latency are the important criteria for this application. The WuRs should be able to react quickly based on the information provided from the sensors thus requiring high data rates. Even WuRs consuming few milliwatts are suitable as long as communication range is greater than 50 m and data requirement is satisfied. The prototype designs by Petrioli *et al.* [39] and Hambeck *et al.* [67] are the ones that fulfill these requirements.

2) Suitable Protocols: Although duty cycling the WuRs on camera nodes will reduce power consumption, it also introduces response latency. To keep the latency at bay, an alternative solution is to use MAC protocols that are based on always on WuRs and continuously monitor the channel while keeping power consumption low (e.g., W-MAC). With regard to routing, a cost effective and reliable multi-hop communication network that relays the monitored information in a timely manner is required so that efficient monitoring of the area can take place.

F. Indoor Localization

In the recent past, robust and accurate indoor localization for navigating has become one of the challenging areas for the WSN community since the GPS does not work indoors. One of the demanding applications of indoor localization besides navigation in shopping malls, user or robot localization, and environment modeling, is support for rescue teams during emergency scenarios. In life-threatening situations such as fire, rescue teams can often lose their orientation in smoky areas due to low visibility.

To increase the indoor localization accuracy within millimeters, these systems employ external reference points known as landmarks, for instance, Wi-Fi access points or ultra-wide band systems for taking extra measurements like Received Signal Strength Indicator (RSSI) or the Time Difference of Arrival (TDoA). These landmarks consume high energy, and either they require a continuous power supply or the batteries have to be changed frequently if always kept on. In catastrophic scenarios when there is no power available from the grid or if the batteries run out, landmarks will be of no use.

Integrating wake-up technology into these landmarks has the potential to extend the lifetime with improved energy consumption. Simon *et al.* [173] presented the idea of developing new WuR enabled wireless landmarks such as smoke detectors. During inactivity, these landmarks can be put into sleep state to reduce unnecessary energy wastage.

1) Matching Prototypes: The requirements for WuRs in the localization case are low power consumption, a communication range of few meters, and data rate in the region of several hundred kb/s. Moreover, there will be many landmarks within a building with devices operating at the similar frequency, therefore, the WuR should provide improved resistance to interference to prevent false wake-ups. WuRs operating in sub-GHz with communication range above 10 m should be preferred.

2) Suitable Protocols: In indoor localization applications, the navigating node will be frequently requesting the data from the anchor or landmarks deployed within the vicinity for updating the localization information. Thus, always on WuR-enabled MAC protocols are best suited for this. However, bi-directional communication is a must as the information will be shared to and from these landmarks. For emergency applications, the key requirement is to deliver messages in real-time and with a high probability of success, a challenging task in wireless sensor networks. To satisfy this requirement, adaptive or opportunistic routing protocols should be adopted to avoid routing holes (caused by nodes that have failed) or seek real-time and valid paths in emergency situations.

G. Asset Tracking

To improve operational efficiency in commercial businesses and to deliver quality customer experience, asset tracking during various phases is essential. Businesses as well as customers, both want to identify, locate and manage their assets in a timely manner. Traditionally, this process was done manually by registering product IDs when the items pass through certain warehouses or locations. A slightly faster method was introduced by use of bar codes for tracking items. However, these methods are time consuming and prone to human error. Recently, RFID technology based solutions have become more preferred choice of tracking items that uses radio signals. The items are attached with passive RFID tags and an active RFID reader is used to send signals to acquire data from these tags. Due to passive nature of the tags, the communication range is usually limited up to a few centimeters and to achieve up to few meters, large antennas are required.

To ameliorate above mentioned issues, active RFID tags have been integrated with wireless sensor nodes [174] such that the integrated tags are able to communicate with many wireless devices which are not limited to readers. The RFID system provides the product IDs while other information is communicated using the main node's radio. Consequently, active RFIDs are too costly and power hungry. Therefore, to bridge the gap between RFID and WSNs, RFIDs can be replaced with WuRs. For example, the WuRs can periodically transmit radio beacons that may contain the product ID and the timestamps forming an "smart object". Moreover, using the built-in selective wake-up method, these beacons can also serve as object selector. Thus, allowing specific nodes to be queried on demand.

Malinowski *et al.* [119] presented the idea of quasi-passive wakeup for asset monitoring. In this work WuRx has been integrated with sensor nodes acting as tags. Whenever the base station queries the tags for events, the wake-up receivers compare the signals against a threshold before activating the main CC2500 radio. If there are no queries, the main radio goes into sleep mode and the WuRx is kept active consuming only 25μW of power. Another specialized tag embedded with wake-up radios and sensors has been recently developed [57] for indoor and outdoor asset tracking. The design is extremely power efficient, low cost and supports dual frequency for communication.

1) Matching Prototypes: To realize wake-up radio based enhanced smart objects long-term operation is an essential requirement. Energy harvesting WuRs such as those proposed in [93], [95], and [99] are suitable alternatives for enabling autonomous long-term operation with minimum maintenance cost.

2) Suitable Protocols: There are two types of nodes utilized in asset tracking; the gateway that is connected to the on-line database and the reader nodes associated with each type of items. To successfully locate these objects, the bi-directional communication mechanism is essential where the gateway can query the reader nodes by requesting information while the reader nodes can respond through their WuRs. On the data collection side, energy-efficient and low-power routing protocol is needed for continuous asset tracking applications. Moreover, in storage facilities such as warehouses where hundreds of sensor tags equipped with WuRs might be present, packet losses and interference will be an issue. Therefore, robust algorithms to counteract this issue needs to be considered. One possible solution is to use multi-channel protocols with the node-addressing feature.

H. Wearables

Nowadays, wearable electronics have the huge potential to enhance people's lives every day. New devices like activity trackers, smart bracelet, smart clothes have appeared in myriad, bundled with appealing Apps and motivating people to be always looking forward to new services. Similar to most of the battery operated devices (e.g., smartphones), wearable electronics tackles the need to prolong the battery autonomy as long as possible as well as keeping the size small for comfortable wearing. The challenge is even harder if considering that most of the tasks required by wearable devices are data-streaming oriented (e.g., headphones, trackers, fitness equipment) and energy efficiency is a key for such devices.

The presence of WuR methods would enhance the device reducing remarkably the energy spent in idle time, when the user is not ready or not connected to the specific device, or not requesting for a specific service. Strategies, where wearable devices are combined with ultra-low power wake up radio have been already presented in [175]. Moreover, context aware applications can decide which wearable object need to be activated avoiding overlapping of services when not needed. Typically, wearable objects are connected using a well known and widespread wireless standard (e.g., Bluetooth Low Energy) to a smartphone, that is used as a central device for processing and forwarding the information to the Internet. Considering that nowadays, smartphones follow owners almost all the day, the communication range of the WuR is not an issue and very low standby power consumption can be achieved.

1) Matching Prototypes: Wearable electronics share some characteristics typical to the WBANs, and considering the short distance, potentially several WuR designs reviewed in this survey could satisfy the application requirements, such as [36], [66], [72], [73], and [99]. Nonetheless, most of the wearable devices offer BLE connectivity and some are equipped with Low-Power Wi-Fi. A WuR technology design in the 2.4 GHz such as one in [96] could facilitate in future the transition towards a comprehensive radio-on-chip which includes a wireless standard and WuR technology.

2) Suitable Protocols: There are a few WuR enabled MAC protocols specifically designed for wearables applications, and to the author's knowledge none are specifically integrated into a standard like BLE or low-power Wi-Fi. To offer high data rate and low latency, a MAC could intensively be called by the wake-up event. Protocols such as those presented in [42] and [133] are suitable for the wearable scenario and offer insights for an integration in Bluetooth radio protocols.

I. Smart Grid

Microgrids is a new trend for achieving energy efficiency in the distribution of the electrical energy. It is revolutionizing the normal electrical grids within the Smart grids. Realtime control services for monitoring the quality of the power distributed from big power generation plants toward small and distributed network make information and communication technology more crucial than in the past.

One of the main challenges of the smart grid applications is relying on efficient communication infrastructure and service. Communication between measurement points is often realized using heterogeneous technology, both wireless and wired. Among these, power line communications (PLC) is a straightforward non-wireless choice. Several wake-up mechanisms that share similar medium, requirements, and protocols have been already proposed [176], [177].

A wake-up based approach can be implemented with a very simple and low-power device that constantly observes the communication channel and informs a host system whenever activity is detected. Since the power consumption of the wake-up is lower than PLC receiver, the overall energy consumption of the communication in the microgrid is drastically reduced.

1) Matching Prototypes: Micro-grid communication often includes heterogeneous technologies. Some of the prototypes that suit smart grid requirements are presented in [36], [67], and [178], while non-RF wakeup circuits such as those in [176] and [177] also exists even if with features tailored for cable communication [177].

2) Suitable Protocols: Protocols for wireless communication in smart grids may either report periodic or on-demand data with various traffic loads. This requires also fast responsiveness at the lowest energy cost. MAC protocols, therefore, should focus on the latency optimization and on the multi-hop characteristic of the network. In these cases, protocols such as PTW, AWD-MAC, and STEM-B are suitable candidates. For the wake-up mechanism developed over PLC (on cables), the protocol needs tight synchronization and the one proposed in [176] is suitable for the purpose.

J. Discussion

This is certainly not an exhaustive list, with are many other applications that can benefit from WuR technology including building automation, smart lighting, remote keyless entry, aerospace to name a few.

Depending on application demands, the requirements for low power WuRs differ. For some applications, a high data rate is essential, while for others long communication range is of importance.

Table XII provides an overview of different application requirements, which can be used as a reference for system developers to assist in categorizing and choosing the appropriate low power WuR. However, one should note that these requirements are not meant to be strict, but rather offer guidelines that one should keep in mind while designing WuR based systems.

As can be seen, the health-care case has the highest demand for data rate because of possible multimedia applications and most stringent power requirements. The highest requirement for communication range is given in the smart city application case, closely followed by wildlife monitoring applications. Only health care applications have moderate

TABLE XIII
SUMMARY OF ISSUES, CHALLENGES, AND OPPORTUNITIES FOR WAKE-UP RADIO BASED HARDWARE AND SOFTWARE DESIGNS

Category	**Dimensions**	**Issues / Challenges**	**Opportunities**
Hardware Design	Cost and Technology Integration	-short communication range -high deployment cost -separate radio modules	-small form factor designs -cheaper SoC -single chip packaging
	Power Demand	-always on receivers -low receiver sensitivity -non-negligible listening power -reduced data rate -high transmission power	-design of energy harvesting WuRs with low latency -ultra low power transmitter designs -novel hardware design with short and long range capabilities -design of low power, high sensitivity WuRs
	System Architecture	-no unified system and networking architecture	-WuR designs with multiple integrated sensors -modular architecture for easy integration -flexible and open source designs
Software [Protocol Designs]	Channel Sharing	-static channel assignment -asymmetric network thus mismatch of transmisson ranges	-multichannel MAC and routing protocols -dynamic spectrum selection -dynamic channel handover -WuR integration with cognitive radios
	Synchronous WuR-MAC	-time synchronization	-synchronous transmission over WuR -efficient time synchronization mechanism with low overhead
	Adaptive Protocols	-static network parameters -non-adaptive	-design of traffic adaptive protocols -dynamic route maintenance
	Mobility	-static nodes -unstable mobile routes	-design of mobility based routing -need for novel topology aware routing with minimum overhead
	Interference and Coexistence	-high interference with nearby in-band devices	-multichannel MAC and routing -dynamic channel hand-over mechanisms -robust wake-up beacon modulation techniques
	Standardization	-none available	Requires standardization of: -frequency -channel availability -wake-up beacon format -hardware design

sensitivity requirements owing to the shorter communication range.

Generally, all applications demand node addressing capability in order to query particular nodes.

Further applications can be realized if wake-up radios are designed with standalone devices. An integration into transceivers as a substitution for built-in wake-on-radio mechanisms can further optimize these applications. Finally, low power consumption for WuRs in the ultra-high frequency (UHF) band offers a vast number of new services and applications.

IX. OPEN ISSUES, CHALLENGES AND FUTURE RESEARCH DIRECTIONS

This section presents some of the main issues and challenges that must be addressed while designing systems based on WuRs. The challenges are not only related to hardware designs but also to the design and efficiency of upper layers of the stack. We then discuss some of the research directions that can be taken to mitigate these issues as discussed next and presented in Table XIII.

A. Hardware Design

The evolution of the WuR technology is mainly driven by advancements in core technology and the demand for ever-less power consumption.

1) Cost and Technology Integration: Cost is one of the major factors, which is taken into consideration when designing and deploying large scale WSNs. So far, the small form factor and low hardware cost have been the key success indicator for WSNs. With the inclusion of WuR, the overall cost is expected to rise and can become one of the hurdles of this method. Further, the cost of designing ultra-low power WuR is still challenging. Current WuR have a shorter communication range than the traditional radios, making it difficult to align coverage of these two radios. For wide area coverage, high-density deployment will be required leading to higher maintenance costs. Recently, to address this issue Magno *et al.* [179] have proposed a new IoT node integrated with LoRa technology and energy harvesting wake-up receiver for long and short range networking. Another design that fuses wake-up radio and BLE technology with energy harvesting has appeared in [96].

Most of the presented features, such as addressing and in- or out-of-band communication, need to be implemented in a single chip with the main radio. Keeping a dual radio mechanism using separate components is expensive for IoT device production. This also includes the RF front-end circuits whose WuR performance mostly depends on the chip design. The possibility to have everything pre-assembled or packaged in a well-characterized module or component will pave the way to create a mass diffusion of such technology. An integrated design including the non-volatile baseband processor with wake-up identification receiver and power management module has been recently proposed in [118]. Although the architecture has been tested only using simulations, it opens up new hardware design opportunities.

2) Power Demand: In WuR based systems, always-on WuRs constantly dissipate energy, thus designing a transceiver that consumes orders of magnitude less than the main radio is necessary. The power demand of WuRs is also dependent on other factors such as reception sensitivity and data rate, which dictates the radios performance. All these factors must be considered and the trade-offs among them should be exploited.

While passive wake-up radios are an attractive and alternative means to save energy, it also poses few challenges. Harvested energy is very sensitive to environmental conditions and where energy sources are not always available, the wake-up procedure may be delayed. For delay-sensitive applications, such designs may not be suitable. Therefore, an open issue is how to reduce this delay with passive systems. Recently Mahapatra *et al.* [180] have investigated how to use energy harvesting based wake-up radios together with error control coding to enhance the performance of networks while reducing carbon footprint.

Further, passive WuRs have shorter communication ranges than active ones. The wake-up signals are transmitted at high power to achieve long range thus incurring high energy cost. This demands low power wake-up transmitter designs similar to wake-up receivers that are simple to implement, turn ON almost instantly, transmit a short WuS and go back to the sleep state. A few works have proposed techniques such as the use of directional antennas [35], antenna diversity [34], and ultra long range RFID [101] to improve the transmission range of these radios.

At the same time, power consumption and receiver sensitivity will still be the major drivers to determine the future direction of WuRs; because they characterize the operating range of WuR. The transmission range of any radio communication will be the major driver for the coming generation of IoT devices. Low power communication is rapidly evolving towards multi-kilometer ranges and low bit-rate schemes. Long range sub-GHz radios such as LoRa [181] or Sigfox [182] are pioneers of this IoT communication revolution. If WuR technology does not advance with its features, it will be hampered in this market.

3) System Architecture: Currently no unified system and networking architecture exists for WuRs to build applications on top. The integration of different types of sensors, energy harvesters, and RFID tags may necessitate new and modular WuR architectures.

B. Protocol Design

Although the notion of wake-up radio eliminates the complexity that is involved with duty cycling MACs, there are many other challenges that need to be taken into account. Power consumption is also affected by the channel conditions, topology of the network, and the routing protocols utilized. Some of these challenges and issues are discussed next.

1) Channel Sharing: Sharing channels between wake-up and main radios must be studied since these two network layers have mismatched transmission ranges, forming an asymmetric network. Designing protocols that are more responsive to channel changes is still an open issue. There are a few research works that have attempted to address this such as CTP-WUR [151], Guo *et al.* [125], and WUR-MAC [130]. One solution to opportunistic spectrum access is using cognitive radios. Recently, cognitive radios have been incorporated in sensor networks [183]–[185]. Traditional radios assume fixed channel allocation and usually operate in crowded unlicensed bands that are also used by other devices making them prone to interference and collisions. Cognitive radios have the ability to opportunistically select the unused spectrum either in a licensed or unlicensed band. Combining WuRs with cognitive radio may enhance the overall system performance by increasing the communication reliability, alleviating collisions and packet losses, and improving the energy efficiency in dense networks. Due to its dynamic spectrum selection mechanism, multiple overlaid networks can also be realized without channel contention.

A few works have proposed dynamic channel selection by integrating wake-up radio with Wi-Fi modules. Specifically, Yoshiwaka *et al.* [186] utilized a frame length detection mechanism with OOK modulation for selecting the appropriate Wi-Fi channel for transmission. Instead of only using wake-up radios for remote triggering, Tang *et al.* [187], [188] have also used it for carrier sensing before transmission by integrating it with WLAN. Standardization of wake-up receiver integration with WLAN has also started [189].

2) Synchronous WuR-MAC: Wake-up radios can also be utilized with synchronous MAC protocols for reducing latency and energy consumption [37]. However, such designs require time synchronization among the nodes. WuRs are even more resource constrained devices than typical motes in terms of processing power, memory, available energy, and communication bandwidth. Thus, complex time synchronization protocols and heavy control overheads may not be feasible and requires careful design.

3) Adaptive Protocols: As seen in Section VIII, WuRs can be utilized for applications that have harsh environments such as structural, animal monitoring or for emergency response where nodes are prone to failures. This may lead to other issues such as transmission failure or long latencies due to poorly designed MAC and routing protocols. To mitigate this, robust and adaptive protocols utilizing WuRs needs to be designed. These protocols should be traffic adaptive, avoid routing holes, and establish new routes dynamically in order to deliver messages reliably and in real-time. WuRs also exhibit shorter communication range than main radios. The design of such protocols is an open research direction.

4) Mobility: Another possible area of research is the consideration of node mobility in wakeup schedule design (e.g., [145] and [146]). Most of the existing schemes assume that the sensor nodes and sink are stationary. Asynchronous and non-collaborative synchronous schemes are good candidates for these scenarios because their lack of coordination requirement makes them robust to network topology changes. In the presence of node mobility, schemes that require coordination may not converge to an optimal schedule or may generate excessive overhead. How WuRs will behave in such situations is still unknown.

5) Interference and Coexistence: The propagation impairments of wake-up radio signals in harsh environments such as forest, industrial or inside human-body also needs to be considered while designing WuR based systems. According to our survey, this so far has not been widely studied. An initial study by Lebreton *et al.* [190] looks into the in-band interference from nearby Wi-Fi devices on a wake-up radio system. The results indicate that wake-up radios are able to maintain high performance in coexistence with external wireless networks while slightly compromising on energy efficiency. Further investigation and study of the aforementioned propagation issues in different settings need to be conducted.

6) Standardization: It is important to remark that there is a clear lack of standardization activities related to the WuR designs such as (i) frequency usage, (ii) available channels, (iii) maximum power below which a radio can be classified as a WuR, (iv) wake-up signal format, and (v) routing topology. To address this, in July 2016, a wake-up radio study group (WUR SG) has been set up within the IEEE 802.11 working group to standardize the above activities [189]. The main aim of this group is to enable an energy efficient data reception for wake-up radios integrated with WLANs without increase of latency. An attempt has also been made to standardize the wake-up radio packet structure so that it is compatible with different technologies in the area of medical applications [41].

X. CONCLUSION

Our survey identifies growing interest across the many facets of the design space of wake-up radios. Available hardware is expanding, with improvements in range, sensitivity and consumption. Protocol stacks are emerging to exploit the novel properties of this technology, opening new application domains. Future work will require coordinated efforts at all levels to address limitations such as the difference in transmission range between a wake-up receiver and a traditional, higher power receiver. Further, issues such as interference must be studied to understand the reliability and robustness of systems incorporating wake-up receivers. Nevertheless, the potential of wake-up receivers to dramatically reduce the power consumption footprint of wireless, battery powered networks has been clearly demonstrated, offering motivation for future work.

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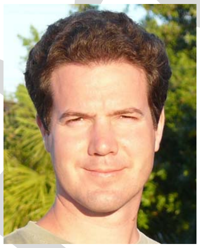

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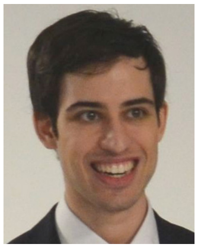

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