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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, discriminating the packet destination using addressing, then switching *on* the main radio only when required. This wake-up receiver (WuRx) 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 (MAC) and routing protocols as well as diverse ways to exploit WuRs, both as an extension of pre-existing protocols 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) is the new Internet frontier providing networks between smart physical objects or "Things", which are embedded with sensors, actuators, and/or processing capabilities. IoT provides novel applications for various fields such as Smart Cities, building automation, domotics, logistics, Smart Grid, e-Health, or agriculture.

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), providing both sensing and actuation capabilities. These devices are usually powered by batteries with restricted size and capacity, 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, to some extent, by the introduction of low-power radios and of *duty-cycling* Medium Access Control (MAC) protocols. 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, reach the goal of the perpetual operation.

A. From Duty-cycling MACs to Wake-up Radios

The main reason why duty-cycling MACs can not extend the lifetime of a node long enough is that the consumption of low-power wireless radios is almost the same when listening for transmissions and while transmitting. For example, the widely used CC2420 radio module consumes 21.8 mA in listening mode and 19.5 mA in the data transmission mode [25]. 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) cannot go arbitrarily low, due to the need for:

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

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

Finally, duty-cycling MAC protocols should either maintain time synchrony to make sure transmitters send when receivers are awake, which induces a time synchronization overhead,

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or in the case of asynchronous operation the MAC protocol should employ continuous (or multiple) transmissions to increase chances of reception. The longer the wake-up period of the receiver, the longer the continuous transmission should be, which dictates 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" in sensor networks [61] each targeting different scenarios and taking 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 used to wake up the main node from the deep sleep mode. Since its power consumption is several orders of magnitude lower than that of a traditional low-power radio, this device can be always-on. One of the modalities in which WuR can be used is illustrated in Fig. 1 (b). When a node has a data packet to send, the WuR is the first to act. It will send a signal known as a *wake-up signal (WuS)* using a *wake-up transmitter (WuTx)*. The purpose of the *wake-up receiver (WuRx)* is to detect this WuS, and generate an interrupt to the main node's micro-controller to switch it from sleep to an active mode. Then, the main micro-controller turns on the main radio transceiver to exchange data packets with the other node in a conventional manner.

Looking at the above simple concept, one might ask why WuR has been developed only recently and not earlier when dozens of duty-cycled MAC protocols were designed. The reason lies in recent improvements in CMOS power consumption, allowing both the implementation of a really low power analog front-end to receive the WuS and also a low power digital part which is used in address decoding.

B. *Wake-up Radio: Benefits and Design Trade-offs*

As mentioned previously, idle listening is the significant contributor to the overall energy consumption of nodes employing duty-cycling. 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, WuRs with an addressing mechanism can be used to solve the issue of overhearing. With addressing, only the intended node will be woken up among the entire neighborhood of nodes.

Since the WuRx can be always-on, the node can operate in a purely asynchronous way without time synchronization, yet turn on the main radio on-demand, without requiring continuous transmissions.

Finally, since the time taken to wirelessly trigger the main node is in order of milliseconds (ms), the latency problem faced by duty-cycling MAC protocols is also reduced, even if not eliminated.

While the concept of having a WuR seems simple and benefits look promising, its 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 poses limits on RX processing and on the components that could be used in the WuRx. Various hardware options had been explored in literature including a wide range of options; even designs that are not radio frequency (RF) based but optical or acoustic.

Strict bounds on power consumption also limit the choice of modulation schemes and receiver complexity, and, as a consequence, limit receiver sensitivity, and ultimately achievable communication range. Since the main radio is triggered by the WuR, this 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), through using out-of-band sub-GHz WuS, to using largely increased WuTx power.

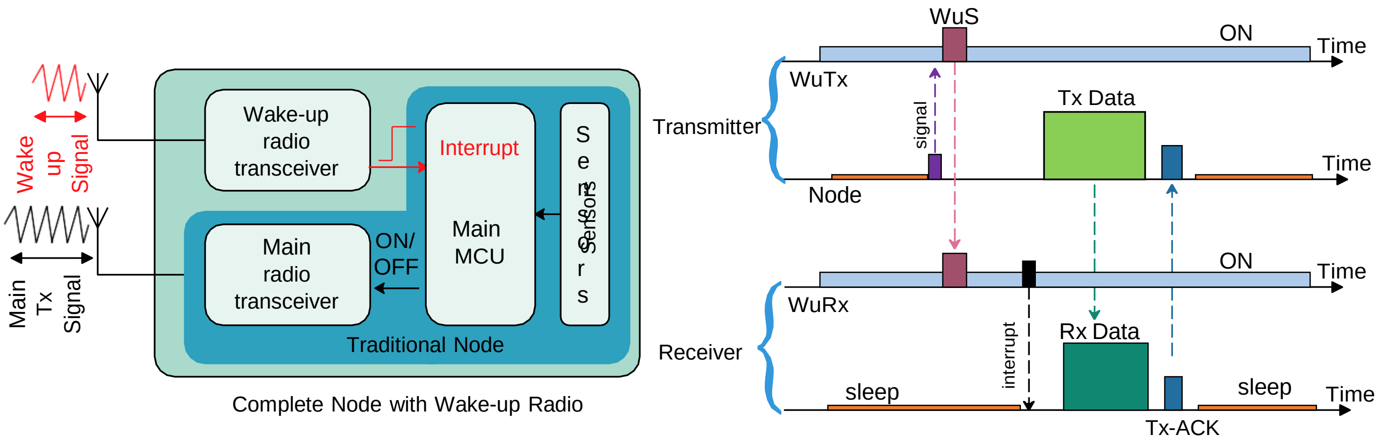
As far as the MAC protocol is concerned, pure asynchronous operation enabled by the always-on WuRx largely simplifies protocol design. However, the development of new WuR specific MAC designs are required, taking into account the dual radio setup of the WuR architecture.

The rest of the paper is organized as follows: Section II depicts the main characteristics of a wake-up radio. Section III provides a generic taxonomy 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 characteristics, respectively. The integration of different media 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 radio. Finally, in Section IX we conclude this survey with some of the open research issues.

II. WAKE-UP RADIO DEFINING CHARACTERISTICS AND REQUIREMENTS

Before we start discussing the different characteristics, some of the common terms used throughout this paper are - *WuTx*: the transmitter on the wake-up module, *WuRx*: the secondary ultra-low power receiver module, *WuS*: the message sent by the WuTx, and *WuR*: the secondary low power module consisting of WuTx and WuRx.

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 fulfill



(a) (b)

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.

the following design requirements. This section also describes some of the shortcomings of using WuRs and outlines ways to mitigate these issues.

(i) **Very low power consumption**. The most important feature of the WuR is its low power consumption in active mode. In fact, as it is needed to add extra hardware on top of the main node, this extra device must consume no more than tens of micro-watts. In fact, the WuR's active power should be below than that of main radio's sleep power [77] to have a positive balance of power saved and used. This is the main specification that drives WuR design.

(ii) **Fast wake-up time**. The node attached with WuR should wake-up with minimum latency upon reception of WuS to overcome multi-hopping overhead and to increase the overall responsiveness of a purely asynchronous network. There are a range of protocols and applications that can benefit from WuR based systems provided that the latency is low. For applications such as health-care that are strict in terms of latency, WuR based system cannot be implemented if the delay introduced by the wake-up procedure takes too long.

(iii) **False wake-ups and Interference**. If all the 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. Therefore, unnecessary activations of the main node should be avoided. For example, if there are ten WuRxs deployed and all of them receive the same 14kHz square wave, then all of them will wake-up, whether it was intended by the transmitter or not. Mainly, there are two possible sources of false wake-ups: 1) nodes waking up while the WuS being intended for another node, and 2) interference from nearby devices operating at the same frequency.

To tackle the first issue, the WuR should have 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.

Secondly, interference and background noise that can result in erroneous wake-ups must be filtered. A WuRx must have enough local processing capability in order to differentiate a WuS from ambient interference, without using the main node's processor. Simple modulation schemes like on-off keying (OOK), pulse width modulation (PWM) or amplitude shift keying (ASK) can be used to reduce devices interfering with each other. Due to the simplicity of these modulation techniques, the receiver structure will be simple requiring low power [65]. A preamble can be used to differentiate noise from a valid WuS, thus avoiding false wake-ups.

In addition, the WuS should 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 has stringent requirements and often leads to over-design to ensure reliable communication in adverse conditions.

WuR should offer tens of meters of communication range to support many application scenarios [29]. Short communication range will make WuR rather impractical as very high node densities will be required to cover a short area in a multi-hop fashion increasing the energy cost. Another side effect of a short communication range is that messages will have to travel a number of hops to reach the sink, increasing the overall network data latency. The wake-up range that can be achieved with most of the current WuR designs is typically around 30m and it can be improved by using techniques such as antenna diversity [60] and directional antennas [108].

(v) **Data Rate**. The overall power expenditure of a node is not only the function of physical layer properties such as carrier frequency, radio architecture, and the choice of the antenna, but also a function of the amount of time the radio spends to deliver the data packet over the air. This time is dependent on the data rate supported by the WuTx and the protocol overhead to establish and maintain the communication link.

Data rate is 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 size of the payload. For WuTx with low data rate, the bit duration and the power required to send the WuS will be significantly higher. Due to longer bit duration, the modulation will be longer keeping the transmitter ON for a longer time. On the WuRx side, the time and the energy required to generate wake-up interrupt will also be significantly higher as the receiver and the demodulation circuitry will be ON until the transmission ends.
A higher data rate can be seen as a way to improve energy efficiency and to achieve a faster wake-up. Although high data rate reduces wake-up latency, long 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, if only used as a triggering device since only few bytes of data transmission is sufficient.

(vi) **Cost and Size**. To integrate into the existing sensor nodes, the WuR should be cost effective. According to [28], to make WuR feasible, the cost of this additional hardware should be in the 5-10% price range of the complete sensor node. However, this is a loose requirement and can be even higher (up to 50%), while still enabling implementations that use WuRs. Also, standard off-the-shelf components can be used to speedup the development and to reduce the overall cost as compared to designing a single chip solution.

(vii) **Frequency Regulation**. Last but not the least, WuR designs should adhere to frequency regulations in industrial, scientific and medical (ISM) band. It should also comply with communication standards such as the maximum allowed effective radiated power (ERP) used to transmit WuS.

III. ARCHITECTURE AND TAXONOMY OF WURS

In this section, we begin by presenting a generic architecture for WuRs and different building blocks that makeup the complete hardware. While presenting the architecture, we discuss the functionality of different hardware components and how these devices can be powered and interfaced with the traditional sensor nodes. Then we move on to presenting the taxonomy of general WuRs and dimensions that distinguish designs from one another. The key dimensions of our generic WuR taxonomy are illustrated in Fig. 3.

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 of these designs. Two distinguished implementation approaches have been identified, i.e., prototypes constructed using off-the-shelf discrete components and implementations that exploit CMOS technology for constructing integrated circuits. The power consumption is one of the driving factors behind the use of WuRs to address the nodes of a network, because of the energy saving that it can virtually provide. Usually, CMOS implementations can achieve better performances, because of the better integration of all the components that are built directly on silicon, i.e., more dense integrated circuits resulting 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 built the circuit resulting in worse average performance than CMOS-based designs.

Fig. 2 illustrates the current architecture and the different functional blocks that build up a complete WuRx as found in the literature. 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 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. 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 microcontroller. 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 multiple energy harvesters that convert the ambient energy into electrical energy. The *Generic Energy Harvester* to power the complete node (including the WuRx, the main transceiver, the main MCU and the sensors) that can exploit different sources of energy such as magnetic, solar, wind, and mechanical vibrations. Also a separate and stand-dalone *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 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 [6], [37], [48], [49], [68], [93], [117]. 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.

B. Taxonomy Overview

Fig. 3 shows the overall taxonomy of WuRs, characterizing different WuR receiver schemes. According to our survey, there are four major dimensions that define the taxonomy: power, addressing, channel and medium of communication. The first dimension is how WuR devices are powered and has a large impact on the overall efficiency of the WSN.

(i) **Passive**. -WuRs do not require a continuous power supply from the battery and can harvest energy either from the ambient environment or from the incoming wake-up signal itself (Fig. 2). If energy is harvested from the WuS, this scenario puts a burden on the transmitter side. The WuTx must modulate and transmit the WuS long enough (usually for few seconds) for the WuRx to detect and accumulate enough energy for powering up the trigger circuitry. The longer the WuTx is ON, the more power is consumed. Moreover, this process requires additional hardware at the WuRx side thus, increasing the circuit complexity and can delay the wake-up of the main node, affecting the network performance by increasing latency and reducing data throughput. Although passive WuRs are energy efficient and offer extended lifetime for sensor networks, they often have a shorter operating range than active WuRs only up to a few meters.

(ii) **Active**. Due to the constraints of passive WuR designs, the research focus has shifted to fully-active WuRs that require a continuous external power supply. For fully-active WuRs the entire circuit is powered externally either using batteries or power from the main node.

(iii) **Semi-active**. In semi-active WuRs, only a minority of the receiver's components such as the correlator, comparator and the decoder require continuous power from the external source while the RF front-end is still passive. The purpose of such designs are to realize WuRs with high sensitivity, providing longer operational ranges with very low power consumption. 89% of the prototypes that we will present in this survey are either active or semi-active based WuRs.

Next, we look at how to specify destination WuRx for initiating communication. The WuS sent by the initiator node can be either *broadcast* "without specific node ID" or *ID-based* "with targeted node ID". A typical WuS packet contains a short preamble followed by the desired node ID. Preamble assists against false wake-ups and provides synchronization.

(i) **ID-Based**. The WuS can contain bit sequence (8-16 bit) for selective node addressing to reduce false wake-up and the overall network energy consumption. After the reception of the WuS, the WuRx checks if the signal is intended for it. If so, it then triggers and wakes up the main node for data reception. This scheme is referred to as ID based wake-up and mostly used for unicast-based systems.

It is to be noted that energy is consumed to decode

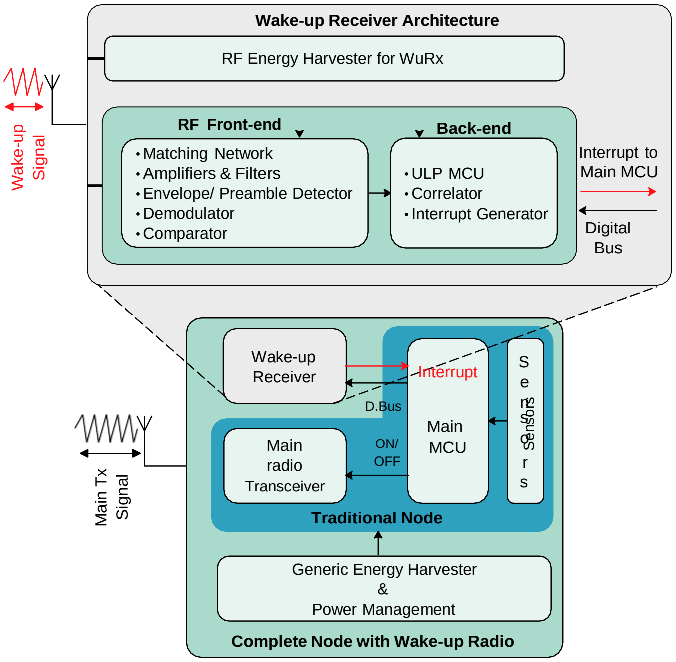


Fig. 2: Exploded view showing the generic Wake-up Radio architecture with Energy Harvesting capabilities.

a wake-up packet usually by an external low-power micro-controller to determine the recipient's identification. Moreover, one should also take into consideration the length of the address code. Although a long address code is more robust against false wake-ups, it requires a long transmit time, hence more power is consumed. Therefore, the address code length should be chosen carefully while maintaining the probability of false wake-ups below a certain threshold.

(ii) **Broadcast**. If the entire neighborhood of nodes receive the wake-up tone, this 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 does not have to decode a wake-up packet to check for the recipient ID and can trigger its main radio transceiver instantly after receiving the preamble. However, this is very expensive in terms of system power consumption as all the neighboring nodes are woken up.

Next, we discuss how the WuR transceiver utilizes the channel for WuS transmission.

(i) **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 since there is no need for a separate antenna.

(ii) **Out-of-Band**. In out-of-band systems usually the main node and the WuRx are equipped with separate transceivers, each operating at different frequencies. For instance, the WuR prototype presented in [6] operates at 868 MHz while the main data radio operates at 2.4 GHz band. Using frequency division techniques like frequency-hopping spread spectrum, this separate channel can further consist of multiple carrier frequencies 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.

(i) **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 most widely used so far and will be discussed in more detail in the next section.

(ii) **Acoustic**. Acoustic based wake-up like ultrasonic and audio signals have also been used in various WuR designs. This medium of WuS transmission does not require any special infrastructure and the audio signals can be easily generated by speakers or smart phones. Authors in [45], [62], [103], [132] have proposed WuR designs based on sound wave for WuS transmission.

(iii) **Optical**. Optical as a communication medium for WuRs has also be utilized for indoor sensor networks [57], [74]. For example, authors in [74] have used Free Space Optics (FSO) for sending WuS. Recently, even communication over *Power Line* has surprisingly benefited from the wake-up mechanism [15], [110].

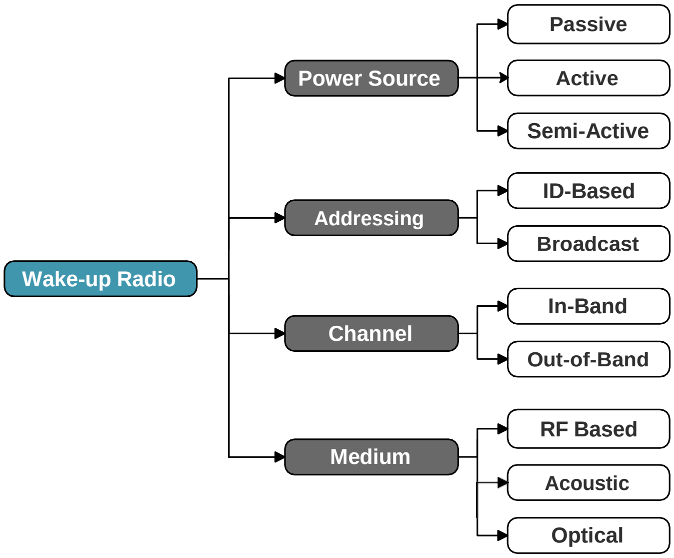


Fig. 3: Taxonomy overview of Wake-up Radios

IV. STATE-OF-THE-ART RF BASED WAKE-UP RADIOS

This section offers a comparison between various RF based WuRs, giving an in-depth view of how these prototypes perform in terms of power consumption, communication range, circuit complexity and reproducibility, and data rate capability. To give a clear picture of the current situation and probable future trends, we have categorized the prototypes based on distinctive features: circuit complexity, address decoding capability, medium of communication, and the implementation (WuR tested using prototype or via simulations). A table summarizing the most significant characteristics of each prototype is provided in Table I, mapping a representative set of prototypes found in the literature to the taxonomy illustrated in Fig. 4.

A. *Defining characteristics of RF WuRs*

So far we have only looked at the generic WuRs. In this section, we focus on the RF WuRs and the main defining characteristics, making them popular and most widely developed and researched. Fig. 4 illustrates some of the main physical layer characteristics divided into six branches: modulation, WuS detection, RF front-end, address decoding, frequency, and technology.

Circuit complexity and reproducibility are the key factors that allow designers to tune and simplify WuRs enabling faster prototyping. However, this is dependent on the modulation technique used for WuS transmission, the architecture of RF front- and back-end, and the choice of frequency. If a complex modulation technique like FSK is utilized, this demands complex circuitry at the RF front-end such as the use of demodulators, mixers, and amplifiers that require extra power. Therefore, simple modulation techniques such as OOK presents an opportunity to simplify the WuRx circuitry and to achieve low power consumption. Comparison of different modulation techniques and how they contribute to WuRx power consumption will be presented in Section V-A.

Another layer of complexity is added when using out-of-band channels for transmission. If the WuR and the main data transceiver are using two 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.

Next, adding node address decoding capability to the WuRx requires additional components at the RF back-end. Usually, a low power micro-controller or correlator is employed for decoding. However, this comes with some trade-offs that will be highlighted in Sections IV-F and IV-G.

Finally, 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 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 smaller in size.

In the remainder of this section, we organize our discussion of different state-of-the art WuR prototypes along three dimensions: circuit complexity (Sections IV-B, IV-C, IV-D & IV-E), address decoding (Sections IV-G & IV-F) and medium of communication (Sections IV-H & IV-I).

B. *Discrete Component Based WuR Proposals*

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

The idea of developing and using ultra-low power radios as WuRs was first conceived by PicoRadio project [98]. Authors propose a 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.

The first proof-of-concept passive WuRx design operating at a frequency of 433MHz was presented by Gu and Stankovic in 2005 [40]. 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 sleep mode is 145 μW while the design was only evaluated through SPICE circuit simulations.

A simulation based super-regenerative WuRx using duty cycling scheme is proposed by Yu et al. [135]. 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. [26] 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.

The most energy efficient low-complexity WuRx prototype proposed to-date is presented by Roberts et al. [101]. This 915 MHz band WuRx achieves a communication range of 1.2 m using 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 when supplied with 1.2 V. However, the WuRx does not support node addressing as per the implementation. Yet another ultra-low power WuRx intended for WBAN is presented in [72]. 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 et al. [101] 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 different 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. Other low-complexity WuRx designs with similar power consumption can be found in [23], [44], [51], [116], [129], [137]

Kamalinejad et al. [53] presented a fully passive 868 MHz WuRx front end that harvests energy from the RF signal to power the circuit. 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. [136] took the idea of Kamalinejad et al. [53] 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

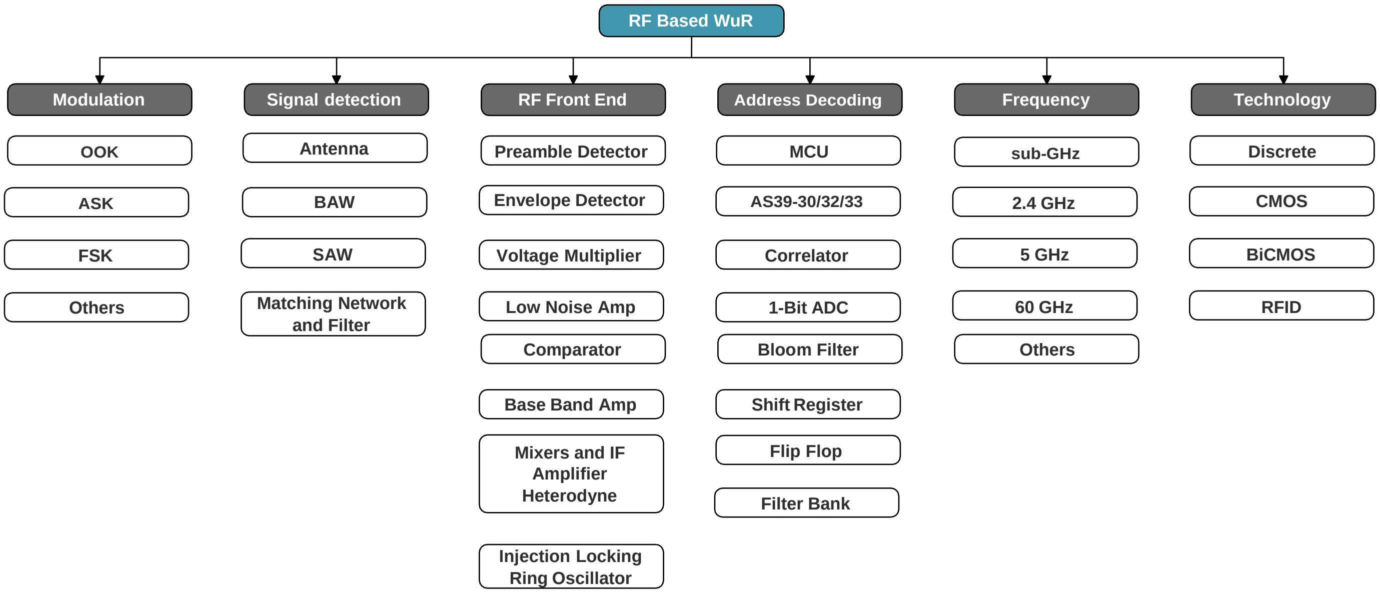


Fig. 4: Defining characteristics of RF-based WuRs with various building blocks

a data rate of 100 kbps at -53 dBm sensitivity. Ammar et al. [5] also proposed a fully passive 868 MHz WuRx that uses Flip Flops for address decoding and dissipates only 13.41 μW. Yet, another passive design by Shekhar et al. [106] operates at 2.45 GHz frequency and exhibits the sensitivity of -23 dBm. At this frequency, the WuRx is able to harvest enough energy to generate the interrupt signal. However, the latter two designs are only evaluated using simulations.

Takiguchi et al. [119] 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.

Petrioli et al. [93] have presented the WuRx using discrete components that supports 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 -86 dBm, while its power consumption is 1620 μW. The line-of-sight communication range is 120 m, the highest range attained using low complexity receiver design. However, this design also have 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.

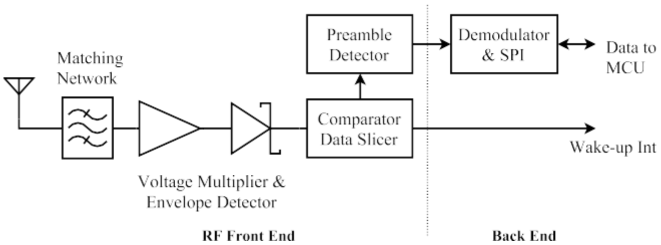


Fig. 5: Simple components based WuRx achitecture

C. *Commercial/Off-the-Shelf WuRs*

There are many proposals in the literature where authors have integrated commercially available WuRx chip AS393X series from Austria Microsystems [118] into their prototypes [11], [12], [37], [86], [96], [117]. The AS393X series 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.

Gamm et al. [37] proposed the first in-band sub-Carrier modulation WuRx system based on AS3932 (Fig. 6). 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. [37] has become the starting point for other AS393X based WuR systems such as the ones presented in [86]–[88]. In [86], Oller et al. proposed WuRx incorporating AS3933 for an 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. Other similar designs based on AS393X WuRx can be found in [96], [117].

Sutton et al. [117] 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 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.

Microsemi based ZL70103 [78] 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.

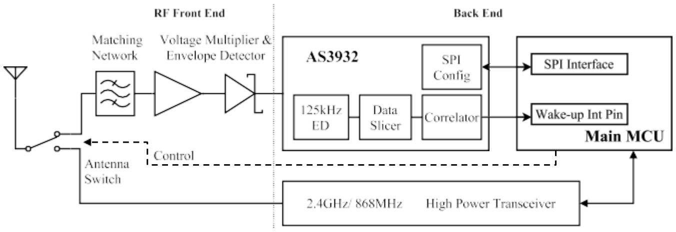


Fig. 6: Wake-up Radio prototypes utilizing Austria MicroSystems AS393x WuRx.

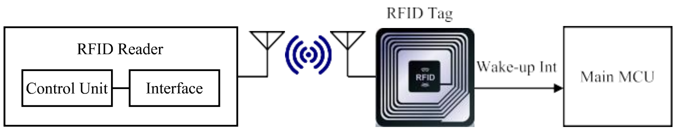


Fig. 7: RFID-based Wake-up Radio prototype

D. WuRs utilizing RFID Technologies

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. 7 illustrates a simple architecture for utilizing RFID technology for WuR systems.

Malinowski et al. [71] 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.

An off-the-shelf active RFID tag based WuRx is simulated in [52]. 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. Ba et al. [8] 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 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. However, this receiver does not utilize addressing to selectively wake up a sensor node.

Since RFID based passive WuR systems usually have a communication range up to few meters only, 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. [22] 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. [27] 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.

From the application point of view, RFID-based WuR systems are suited for mid-range applications. Such applications could be health monitoring, inventory monitoring, or environmental applications as outlined in [8]. Nonetheless, the maximum communication range achieved so far has been 30 m using an active RFID tag [52]. 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 its antennae sizes, the bigger the antenna the more power can be transmitted thus longer 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 a system-on-chips, which may be suitable for wide range of applications.

E. Heterodyne Based WuR Proposals

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. 8). Pletcher et al. [94] 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 [95] 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 2.4 GHz heterodyne WuRx was proposed by Drago et al. [31]. 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.

Another heterodyne ultra-low power WuRx operating at 900 MHz band was proposed in [21]. This passive chip consists of an RF front end and a digital baseband with non volatile memory. The radio block includes a voltage multiplier for rectifying 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.

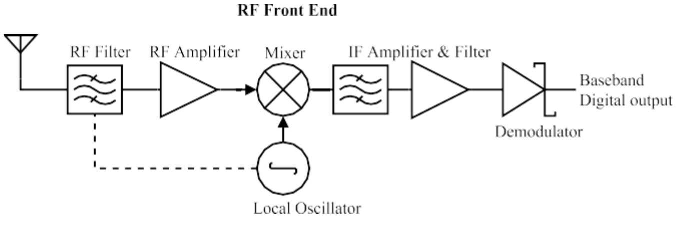


Fig. 8: Generic Block diagram of Heterodyne WuRx

A different heterodyne based WuRx operating in 60 GHz millimeter-wave band for high data rate short-range applications is proposed in [131]. 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 passive 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. [128] 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 heterodyne based WuRx that operates at 5.8 GHz has been reported in [50] but has lower sensitivity of -44 dBm. For the latter two designs, the authors have not published any operational distance.

Cho et al. [24] 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. Other heterodyne based WuRx prototypes achieving power consumption between 22 μW and 100 μW have also been reported in [1], [16], [82], [102], [121].

There are also designs reported in the literature that have power consumption above 1000 μW [12], [58], [111], [122], [124] compared to the ones discussed earlier. The WuRx proposed by Bdiri et al. [12] 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.

Most of these heterodyne based WuRs offer superior sensitivity and data rate, but lack node addressing capabilities and information on an operational range. This category of WuRs also feature highest power consumption of up to a few milliwatts [12], [122] compared to other WuR designs, since heterodyne approach requires some active components such as IF-amplifiers and mixers. It has also been noticed that some of these designs operate in non-ISM bands such as 45 MHz [24] or 1.9 GHz [94] making them inadequate for medical applications.

F. WuRs incorporating Low-Power MCUs for Address Decoding

There are some WuR designs that have used a secondary dedicated low-power micro-controller to decode the address code. An example is shown in Fig. 9, which illustrates 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.

Ansari et al. [6] present a radio triggered wake-up circuit attached to a TelosB node and exploited its main MSP430 MCU for address decoding. The WuTx uses 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 10m for the 500μW transmission power.

A similar approach using separate MCU for address decoding and interference filtering is also reported in [29]. In this prototype, authors have integrated a PIC12F683 MCU to detect and decode a WuS after signal rectification and amplification, and notifies a 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 et al. [11], but has low 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. The results indicate that using AS3932 for address decoding leads to an additional power consumption of 3.9 μW than the MCU.

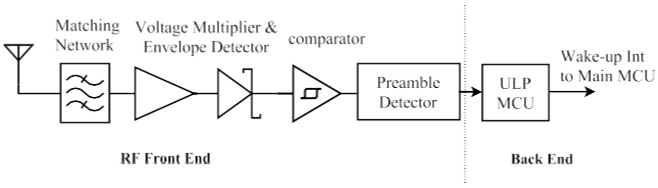


Fig. 9: Wake-up Radios employing ultra-low power MCUs for address decoding and interrupt generation

The sub-GHz WuRx presented by Spenza et al. [113] consumes 1.276 μW in listening mode. The receiver uses OOK modulation and is made of four main building blocks: a matching network, a passive 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. [68], 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.

Other designs that exploit MCU for address decoding while achieving power consumption below 15 μW can be found in [14], [35], [47]. However, these designs do not provide any detail on operational distance that can be achieved with these WuRxs.

It has been observed that introduction of extra hardware for address decoding adds to the overall power overhead and may not be applicable for applications that have strict power requirements. However, due to advancement in miniaturization the power consumption of these MCUs have drastically reduced over the years making it possible to integrate with WuRx while still achieving power consumption below 10 μW.

G. WuRs utilizing Correlators for Address Decoding

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. 10 depicts a simple "matched filter" based parallel correlator concept used to decode address in a WuS.

Mark et al. [127] 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, 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.

Le-Huy et al. [65] also simulated an in-band 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. Other simulated designs can be found in [91], [109].

Hambeck et al. [43] 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 6.4d Bm. At this conditions, the WuRx dissipates only 2.4 μW at supply voltage of 1 V.

Milosiu et al. [80] 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 [83], [100], [120] obtaining power consumption below 3 μW.

H. *WuRs supporting Multi-band Frequencies*

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. [46] propose a low complexity WuRx able to operate selectively at 915 MHz and 2.4 GHz band using different off-chip inductors at the RF impedance matching stage. 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.

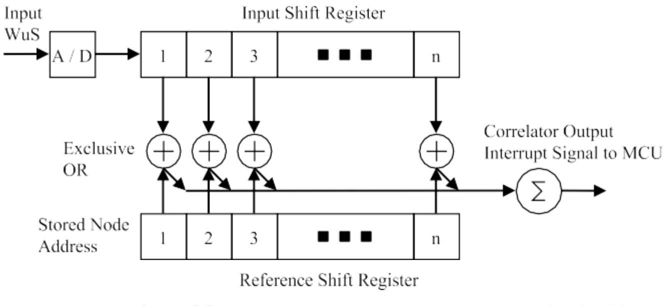


Fig. 10: Node address comparison using “matched filter” correlation detector

Oh et al. [84] present 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 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.

Roberts et al. [99] 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 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 [36]. The Fraunhofer WakeUp-Receiver [36], which is based on 130-nm CMOS technology, operates in the 868 MHz and 2.4 GHz frequency bands and feature -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.

Recently, another dual-band WuRx that operates in 868 MHz and 2.4 GHz band has been proposed in [97]. 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.

I. *Non-RF Based WuR Proposals*

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 only drawback is that some of these devices require 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 II.

Hakkinen et al. [42] 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 coverts 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. [74] 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 [57] 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 [74], FLOW features a 16-bit node addressing capability. However, similar to [74], 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.

Sanchez et al. [103] 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 [132]. 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. [62]. Unlike [132], 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. [45] presents an acoustic WuRx operating at 18 kHz for controlling devices and appliances at home. The audio signal is sent using a smart-phone 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 [9], which operates at 20 kHz audio signals and features node addressing. To reduce the power consumption than that of [45], 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. [17] have developed the 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 $\sim$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.

TABLE I: 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. [98]	Active	-	-	OOK	ANT, MN	LNA	-	CMOS	1	1.9	100	-	10	380	Simulation
2	2005	Gu et al. [40]	Passive	ID-Based	O-O-B	OOK	ANT, MN	PD, ED, VM, LNA	MF	Discrete	-	0.433	-	-	3	-	Simulation
3	2007	Pletcher et al. [94]	Active	-	-	OOK	ANT, MN, BAW	ED, LNA,	-	CMOS	0.5	1.9	40	-50	-	65	Prototype
4	2007	Malinowski et al. [71]	Active	-	O-O-B	OOK	ANT, MN	ED, LNA, VM	-	RFID	3	0.3	-	-65	8	2.8	Prototype
5	2007	Mark et al. [127]	Active	ID-Based	-	OOK	ANT, MN	ED, LNA,	C	BiCMOS	-	2.4	-	-50	-	-	Simulation
6	2008	Yu et al. [135]	Active	-	-	OOK	MN	ED	-	CMOS	1.8	2.4	100	-75	-	56	Simulation
7	2009	Pletcher et al. [95]	Active	Broadcast	-	OOK	ANT, MN, BAW	ED, M-IF	-	CMOS	0.5	2	100	-72	-	52	Prototype
8	2009	Doorn et al. [29]	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. [119]	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. [51]	Active	-	-	OOK	ANT, MN	ED, VM	-	CMOS	1.5	2.4	-	-28	-	1.35	Prototype
11	2009	Ansari et al. [6]	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. [35]	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. [65]	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. [124]	Active	-	-	FSK	ANT	zero-IF, LNA	-	CMOS	1.5	0.915	45	-89	10	2700	Prototype
15	2010	Gamm et al. [37]	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. [31]	Active	-	-	PPM	ANT, MN	M-IF	-	CMOS	1.2	2.4	500	-82	-	415	Prototype
17	2010	Jurdak et al. [52]	Active	-	O-O-B	ASK	-	RFID Tag	-	RFID	3	2.4	250	-95	30	80	Simulation
18	2010	Huang et al. [46]	Active	Broadcast	I-B	OOK	ANT,MN	ED, LNA	-	CMOS	1	0.915/2.4	100	-64	-	51	Prototype
19	2011	Chung et al. [21]	Passive	-	-	ASK	ANT	ED, VM, ILRO	-	CMOS	0.8	0.9	-	-17	-	2.64	Prototype
20	2011	Zhang et al. [137]	Active	-	-	OOK	ANT,MN	ED	-	CMOS	1.2	-	200	-	-	3.72	Prototype
21	2011	Hambeck et al. [43]	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. [120]	Active	ID-Based	I-B	OOK	ANT, MN	ED, LNA	C	CMOS	-	2.4	100	-82	-	-	Prototype
23	2011	Li et al. [131]	Active	-	-	OOK	ANT	ILRO	-	CMOS	1.2	60	1000000	-62	0.2	230	Simulation
24	2011	Marinkovic et al. [72]	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. [101]	Active	-	-	OOK	ANT, MN	ED, LNA	-	CMOS	1.2	0.915	100	-41	1.2	0.098	Prototype
26	2012	Sjoland et al. [111]	Active	ID-Based	-	FSK	ANT, SAW	LNA, M-IF	1B	CMOS	0.8	2.4	250	-92	-	1000	Simulation
27	2012	Yoon et al. [26]	Active	ID-Based	-	OOK	ANT, MN	ED, LNA, PD	1B	CMOS	1.8	0.9	200	-73	-	1100	Prototype
28	2013	Oller et al. [87]	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. [24]	Active	-	-	FSK	ANT	LNA, ILRO	-	CMOS	0.7	0.045	200	-62.7	-	37.5	Prototype
30	2013	Wada et al. [128]	Active	-	-	OOK	ANT, MN	ED, BB,ILRO	-	CMOS	1.5	60	350	-68	-	9	Prototype
31	2013	Francois et al. [47]	Active	ID-Based	-	OOK	ANT,MN	ED, PD	MCU	CMOS	1.2	2.4	250	-	-	5	Simulation
32	2013	Milosiu et al. [80]	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. [84]	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. [96]	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. [58]	Active	-	-	OOK	ANT	ED, LNA, M-IF, H	-	CMOS	1.8	2.4	100	-60	-	1008	Prototype
36	2013	Boaventura et al. [14]	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. [83]	Passive	ID-Based	-	OOK	ANT, MN	ED, BB	C	CMOS	1	2.4	200	-47	-	2.3	Prototype
38	2013	Ba et al. [8]	Passive	ID-Based	O-O-B	ASK	-	RFID Tag	MCU	RFID	-	0.9	1pkt/min	-80	<5	-	Prototype
39	2014	Petrioli et al. [93]	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. [86]	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. [113]	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. [11]	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. [122]	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. [91]	Active	ID-Based	-	OOK	ANT, MN	ED, LNA	C	CMOS	0.9	-	-	-	-	63.98	Simulation
45	2014	Bryant et al. [16]	Active	Broadcast	-	OOK	ANT,MN	ED, M-IF, BB	-	CMOS	0.75	2.4	250	-88	-	50	Prototype
46	2014	Abe et al. [1]	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. [53]	Passive	Broadcast	-	OOK	ANT, MN	ED, LNA, VM	-	CMOS	-	0.868	100	-33	-	0.5	Simulation
48	2014	Oller et al. [88]	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. [50]	Active	-	-	ASK	ANT	ED, BB, LNA, M-IF	-	CMOS	3.6	5.8	0.014	-44	-	36	Prototype
50	2014	Donno et al. [27]	Active	ID-Based	O-O-B	-	ANT, MN	UHF RFID Tag	MCU	RFID	1.8	0.868	-	-	22	54	Prototype
51	2014	Fraunhofer [36]	Active	ID-Based	-	-	ANT, MN	-	-	CMOS	2.5	0.868/2.4	1	-80	-	7.5	Prototype
52	2015	Moazzeni et al. [82]	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. [81]	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. [99]	Active	ID-Based	-	-	-	-	-	Discrete	2.5	0.433/0.868	-	-	-	5	Prototype
55	2015	Zgaren et al. [136]	Passive	-	I-B	OOK	ANT, MN	ED, LNA	-	CMOS	1.2	0.915	100	-53	-	0.2	Prototype
56	2015	Prete et al. [97]	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. [106]	Passive	-	I-B	-	ANT, MN	ED, VM	-	CMOS	-	2.4	-	-23	-	-	Simulation
58	2015	Sutton et al. [117]	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. [102]	Active	-	-	OOK	ANT, MN	ED, LNA, M-IF	-	CMOS	0.5	2.4	10	-97	-	99	Prototype
60	2015	Ammar et al. [5]	Passive	ID-Based	-	OOK	ANT, MN	ED, VM, LNA	FF	Discrete	0.9	0.868	100	-54	-	13.41	Simulation
61	2015	Chen et al. [23]	Active	-	-	OOK	ANT, MN	ED, BB, COM	-	CMOS	0.8	2.4	100	-50	-	4.5	Prototype
62	2015	Taris et al. [121]	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. [129]	Active	-	-	-	ANT, MN	ED, VM	-	CMOS	-	-	10	-	-	0.05	Simulation
64	2015	Sumanthi et al. [116]	Active	-	-	OOK	ANT, MN	ED, VM, LNA, PD, COM	-	Discrete	-	0.433	128	-32	-	-	Simulation
65	2015	Chen et al. [22]	Passive	ID-Based	O-O-B	-	-	RFID Tag	AS	RFID	-	0.9	-	-86	9.4	-	Prototype
66	2015	Bdiri et al. [12]	Active	ID-Based	-	OOK	ANT, MN	ED, M-IF	AS	Discrete	2.5	1.5	-	-60	82	5247.5	Prototype
67	2016	Magno et al. [68]	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. [109]	Active	ID-Based	-	O-QPSK	ANT, MN	PD	C	CMOS	1.8	2.4	250	-	-	28.2	Simulation
69	2016	Roberts et al. [100]	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. [44]	Active	-	-	OOK	ANT, MN	LNA, BPF, BB, COM	-	CMOS	1	0.315	10	-58.5	-	1.36	Simulation

TABLE II: 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. [42]	Active	-	O-O-B	OOK	Photo Diode	LNA, BPF, COM	-	Infrared	3	-	-	-	6∼30	12	Prototype
2	2010	Mathews et al. [74]	Active	-	O-O-B	OOK	Photo Diode	LNA, C	-	Optical	3.3	-	2	-53	15	317	Prototype
3	2012	Kim et al. [57]	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. [103]	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. [132]	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. [62]	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. [45]	Active	-	O-O-B	PWM	Microphone	LNA	AS3933	Audio	3	18	-	-	7.5	56	Prototype
8	2016	Bannoura et al. [9]	Active	ID-Based	O-O-B	ASK	Microphone	BPF, LNA	AS3934	Audio	3	20	-	-	10	45	Prototype
9	2016	Carrascal et al. [17]	Active	ID-Based	O-O-B	ASK	Solar panel	ED,C	AS3933	VLC	2.4	21	1.12	-	7∼14	19.2	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.

V. COMPARATIVE 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 so far in terms of power consumption, sensitivity, data rate, communication range and the modulation scheme used, regardless of their specific technology. This comparison will then be used to recommend which prototypes are suitable and meet the requirements of various applications and is 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 I, it can be noted that most designs use either envelope detector based On-Off keying (OOK) or non-coherent Frequency-Shift-Keying (FSK). Due to simplicity of 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 [68], [72], [113]. It is evident from Table I that most of the concepts that have power consumption below 10μW are using OOK modulation.

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 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 et al. [65] 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. [109] 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. [6] 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. [31]. 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. [100] 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. 11 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 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. 11, the lowest power consumption that has been achieved so far has been 98 nW [101], 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 70 prototypes that we have surveyed for RF based WuR for those that power consumption and sensitivity values were provided, only 23 prototypes [11], [14], [21], [23], [36], [37], [51], [53], [65], [68], [72], [80], [81], [83], [84], [87], [97], [100], [101], [113], [117], [128], [136] were able to achieve power consumption below 10 μW, where [101] and [84] reached an outstanding power consumption around 100 nW.

Regarding the requirements in Table V for different applications, it can be seen that for short-range communication such as WBAN, five WuR prototypes [72], [84], [100], [101], [136] (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 [80], [81] (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. 11 is useful for understanding key design trade-offs. For example, most designers [12], [122], [124] 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 [101] while the other design is not [12]. Out of these, there are two designs, one based on CDMA [100] and the other using FSK modulation [1] 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. 12 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 [67], 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 [87] to 100 kbps [23] in an OOK receiver.

As can be seen, there are fourteen designs [16], [24], [31], [37], [47], [82], [83], [93], [109], [111], [128], [131], [134], [137] that have been able to reach a data rate above 200 kbps. Out of these, five [37], [47], [83], [128], [137] have a power consumption below 10 μW.

From the application perspective, there are few designs [37], [47], [83], [128], [137] (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 [131], however, it may not be suitable for WBAN due to its high power consumption of 230 μW. But, 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 [5], [6], [14], [23], [35]–[37], [47], [53], [68], [72], [81], [83], [84], [87], [100], [101], [113], [117], [128], [136], [137] (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, Sensitivity, and Power Consumption*

So far we have only looked at the prototypes that have been able to satisfy either two of the requirements: sensitivity versus power or data rate versus power. While some prototypes may be able to achieve high sensitivity and data rate with minimum power consumption, they may still not be able to communicate further than few meters making them unsuitable for long range applications such as in the case of smart city.

In this section we will take a thorough look at all of the requirements for different WuR based applications: (1) data rate, (2) power consumption, (3) sensitivity, and (4) range, and classify which of these prototypes fit the best for each.

Figures 13 and 14 show the maximum achievable communication range reported for different WuR prototypes in terms of their sensitivity and 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.

There are few different trends that can be observed from Figures 13 and 14. First, there are few designs [82], [124] that have very low sensitivity but at the same time only having communication range up to few tens of meters. Secondly, there are two prototypes [12], [93] that achieved a communication range of 120 m and 80 m with sensitivity level of -83 dBm and -60 dBm, respectively (labeled as B and C). However, there is

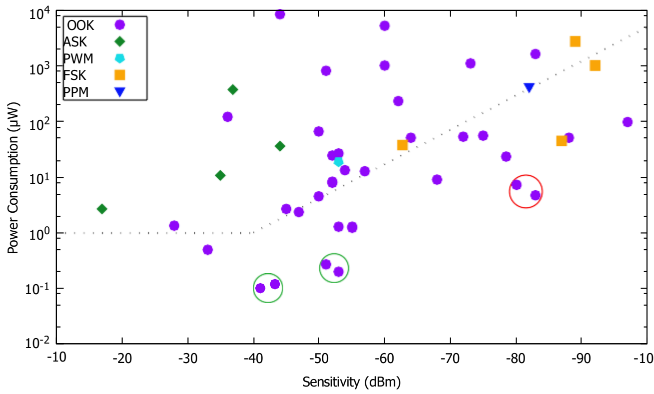


Fig. 11: Sensitivity of low power RF based wake-up receivers vs. Power consumption

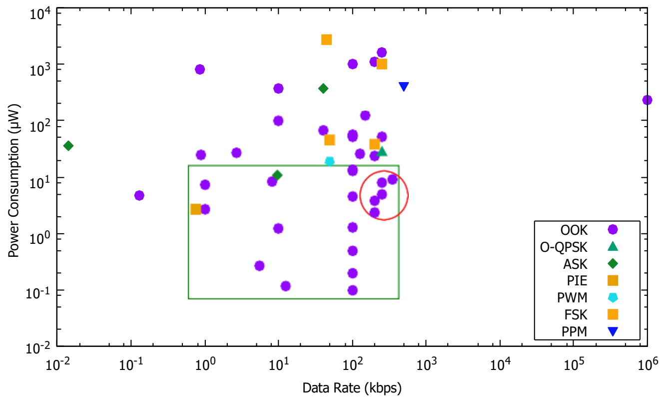


Fig. 12: Data Rate of low power RF based wake-up receivers vs. their Power consumption

a clear trade-off in terms of energy as the WuR consumes very high power of 1620 μW and 5247.5 μW, respectively. Referring to Table I, so far, only two of the reported designs [43], [80] have achieved a line-of-sight distance of over 200 m with low-power consumption. The design in [43] achieved a distance of up to 304 m at sensitivity of -71 dBm (6.4 dBm transmit power) with a data rate of 100 kbps and consumes only 2.4 μW in listening mode. The design by Milosiu et al. [80] was able to successfully communicate up to 1200 m, with sensitivity of -83 dBm while consuming only 4.75 μW at a data rate of 128 bps.

From the application point of view, WuR prototypes with communication range between 30 m to 50 m (labeled as cluster A) [37], [68], [86], [113], [117] satisfy all the above requirements for mid-range applications. For the WBAN case WuR concepts [37], [47], [83], [128], [137] fulfills 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.

Discussion: The main characteristics of all ultra-low power WuR are sensitivity, data rate 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.

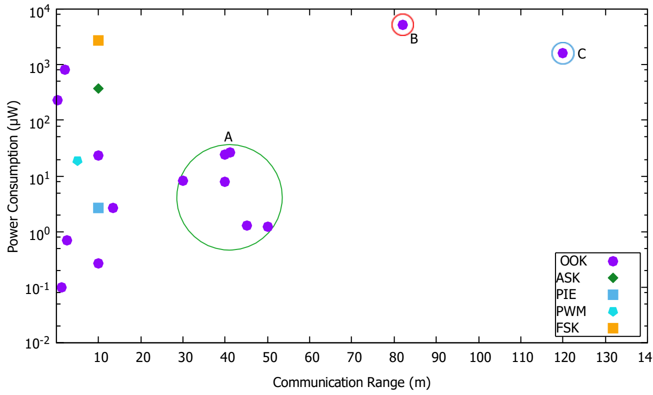


Fig. 13: Communication Range of RF based wake-up receivers vs. their Power consumption

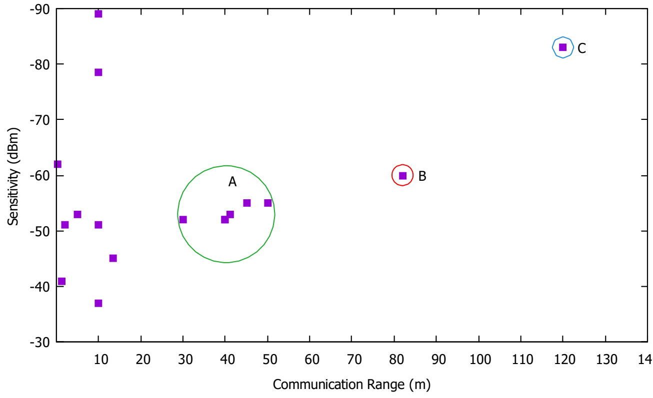


Fig. 14: Communication Range of RF based wake-up receivers vs. Sensitivity

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 the WuR technology has been focused on improving hardware components to achieve better 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 addressing MAC, we address properties both general to wireless medium access and specific to WuR. The key dimensions of our MAC taxonomy appear in Fig. 15 while Table III summarizes the different WuR based MAC protocols designed so far.

A. Taxonomy of WuR-based Medium Access

MAC protocols typically divide themselves between on-demand and scheduled, with a majority of existing WuR protocols falling into the former category due to its 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 resources 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.

The first concern we address is identifying which pair of nodes is allocated the wireless channel based on who is the *communication initiator*: the transmitter, the receiver or bi-directional.

(i) **Transmitter-Initiated**. In a Transmitter-initiated protocol, the node that has data to send initiates communication (Fig. 16(a)). It first sends a wake-up 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) **Receiver-Initiated**. In Receiver-initiated systems (Fig. 16(b)), the burden of starting a communication event falls to the receiver, specifically with the node,

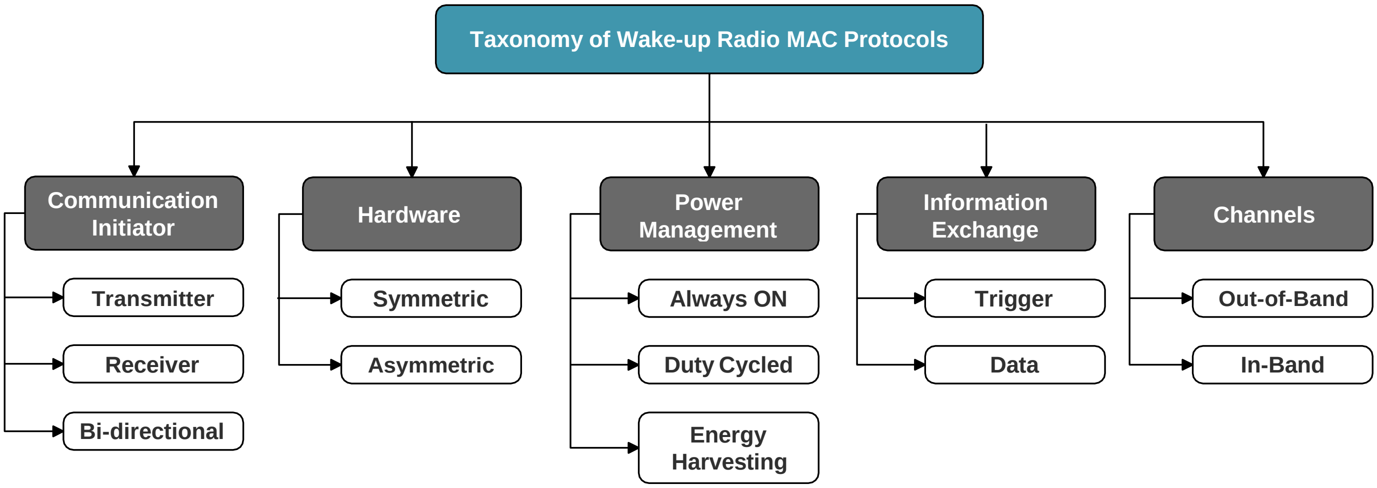


Fig. 15: Taxonomy of Wake-up Radio based MAC Protocols

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 into sleep mode. This communication modality is most effective when transmissions are infrequent, and collisions at the receiver are unlikely.

(iii) **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) **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) **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. 16(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) **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) **Duty Cycled WuR**. To further reduce power consumption, the wake-up radio itself can be duty cycled (Fig. 16(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) **Energy Harvesting WuR**. As mentioned before 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. 16(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.

Next, we consider the actual information being exchanged over the WuR.

(i) **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) **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) **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.

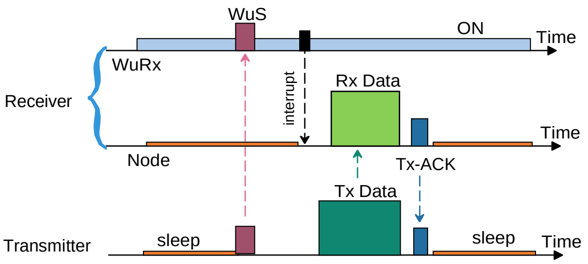
(ii) **Out-of-Band**. Multiple channels, instead, can reduce interference and increase bandwidth, but at the expense of additional coordination between senders and receivers both in time, as mentioned previously, and also across the space of the channels. In most of the WuR-MAC protocols, the bandwidth 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 specific proposed protocols along three dimensions: transmitter-initiated, receiver-initiated and bi-directional. Within each of these, we further sub-divide the discussion across in-band and out-of-band approaches, also offering the categorization of the protocols along the lines mentioned here.

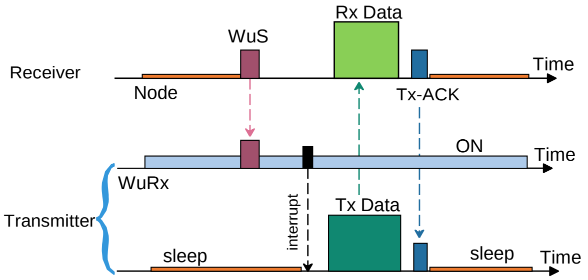
B. Transmitter-Initiated MAC Protocols

In this section, we present various 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.

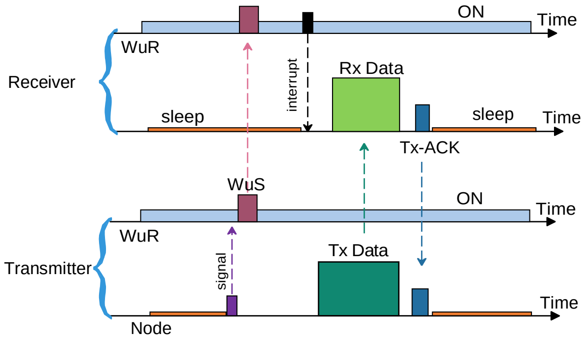
***Out-of-Band*:** **STEM** [104] is one of the first transmitter-initiated protocols that separates the data transmission channel from the wake-up channel by using a dual radio approach on separate frequency bands. Two variants exist in STEM. In STEM-T, a tone is sent which wakes up all the nodes in 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



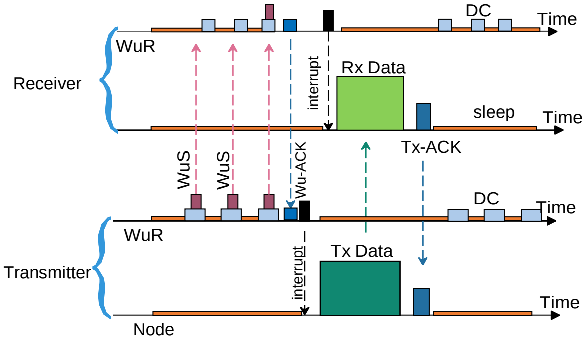
(a) Transmitter-Initiated MAC.



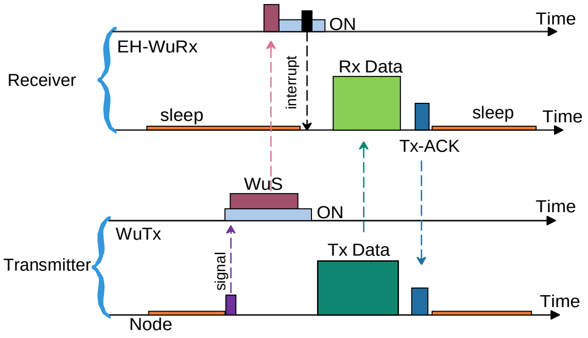
(b) Receiver-Initiated MAC.



(c) Symmetric WuR System.



(d) Duty Cycled WuR.



(e) Energy Harvesting WuR System.

Fig. 16: Wake-up Radio communication schemes.

TABLE III: WAKE-UP RADIO BASED MAC PROTOCOL DESIGNS

Protocol	Year	Initiator	Hardware	Power Management	Information Exchange	Channels	Key Novelty	Implement^{n}
Guo et al. [41]	2001	Bidirectional	Symmetric	Always ON	Trigger	Multiple	-Embedding channel information in WuS	Simulation
STEM-T [104]	2002	Transmitter	Symmetric	Duty Cycled	Trigger	Out-of-Band	-All neighbors woken up	Simulation
STEM-B [104]	2002	Transmitter	Symmetric	Duty Cycled	Trigger	Out-of-Band	-Addressed Beacon	Simulation
PTW [133]	2004	Transmitter	Asymmetric	Duty Cycled	Trigger	Out-of-Band	-Broadcast wake-up -Addressing on data channel	Simulation
Miller et al. [79]	2005	Bidirectional	Symmetric	Duty Cycled	Trigger	Multiple	- Wake up scheduling	Simulation
SLAM [56]	2007	Bidirectional	Symmetric	Energy harvesting	Trigger	Multiple	-Energy harvesting by all nodes	Simulation
WUR-MAC [70]	2009	Transmitter	Asymmetric	Always ON	Trigger	Out-of-Band	-CTS / RTS on WuR channel	Simulation
DCW-MAC [75], [76]	2011-14	Transmitter	Asymmetric	Duty Cycled	Trigger	In-Band	-Single trasmitter for trigger and data -Separate WuRxs	Simulation
VLPM [123]	2011	Bidirectional	Symmetric	Always ON	Trigger	Multiple	-Bidirectional wake up	Simulation
On-Demand MAC [3], [4]	2011	Bidirectional	Symmetric	Always ON	Trigger	Multiple	-Bidirectional wake-up	Simulation
Blanckenstein et al. [13]	2012	Transmitter	Asymmetric	Always ON	Trigger	In-Band	-Node clustering -TDMA on main radio	Simulation
WhMAC [73]	2012	Bidirectional	Symmetric	Always ON	Trigger	Multiple	-TDMA on main radio	Simulation
WUR-TICER [63]	2013	Transmitter	Asymmetric	Energy harvesting	Trigger	In-Band	-Energy harvesting by all nodes	Simulation
GWR-MAC [54], [55]	2014	Bidirectional	Symmetric	Always ON	Trigger	Multiple	-Bidirectional wake up	Simulation
MH-REACH-Mote [22]	2015	Receiver	Asymmetric	Energy harvesting	Trigger	Out-of-Band	-Passive RFID	Testbed
DoRa [66]	2015	Receiver	Asymmetric	Energy harvesting	Trigger	Out-of-Band	-Energy harvesting -Base station wakes up the neighbors	Simulation
AWD-MAC [64]	2015	Receiver	Asymmetric	Always ON	Set of Triggers	In-Band	-Wake up multiple neighbors	Simulation
BATS [34]	2016	Receiver	Asymmetric	Duty Cycled	Trigger	Out-of-Band	-Supports Mobility	Testbed

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.

Similar to STEM-T, Yang et al. [133] 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. Another transmitter-initiated MAC protocol leveraging WuRxs is proposed by Mahlknecht et al. [70]. WUR-MAC is based on same multi-channel principle and uses RTS and CTS handshake mechanism. The WuRx uses RTC/CTS mechanism for channel reservation purposes while the main transceiver is only used for data communication at higher bandwidth. WUR-MAC supports both, point-to-point and broadcast communication.

The idea of using WuRxs outside WSNs has also been proposed. For instance, in [107] a technique called *wake-on-wireless* is introduced to extend the battery lifetime of a personal digital assistant (PDA)-based phone by reducing its idle power while waiting for an incoming call.To the PDA, authors added an out-of-band secondary low power radio called *MiniBrick* that enables the wake-on-wireless mechanism. Once awake, the PDA accepts the call on its primary higher rate, high power data channel. Experimental results show that the battery lifetime of these devices can be improved by 115 percent over a popular IEEE802.11b-enabled PDA.

In-Band: Analogous to STEM and PTW, the work in [75], [76] also duty cycles the WuRx, but uses in-band approach for communication. In DCW-MAC, the main radio is used for both, sending the WuS 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.

Le et al. [63] have proposed the **WUR-TICER** MAC protocol that can operate by harvesting energy from the ambient environment. The protocol is based on nano-watt WuRx proposed in [69] 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.

Energy efficient node clustering using WuRxs for WBAN sensors with similar readings is presented in [13]. To eliminate idle listening and channel contention, an always on WuRx is attached to a main radio that utilizes Time Division Multiple Access (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.

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.

Out-of-Band: **MH-REACH-Mote** is a MAC protocol designed for passive RFID-based WuR systems supporting multi-hop wake-up sensor networks [22]. In it, the WuTx on the sink wakes up all nodes in the vicinity of the sink. Any node that was woken up by the sink sends 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 longer wake-up signal duration (between 5s-10s) to accumulate enough energy in order 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 the 1-hop are activated thus contributing to extra energy overhead.

DoRa [66] offers another WuR-MAC protocol that builds upon the foundation of the receiver-initiated paradigm for the realization of Energy Harvesting WSNs. In the proposed mechanism, no RTS/CTS 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-Mote, a strong wake-up signal is required in order to harvest enough energy to activate the nodes leading to high data latency time.

Finally, the first mobility-based WuRx system using the receiver-initiated paradigm has been proposed in the BATS project [130]. Authors have investigated the potential of ultra-low WuRs carried by the bats to monitor contacts or encounters between individuals and to track their routes at high spatial and temporal resolution [32]–[34]. To support multiple mobile nodes and to prevent the collisions at the receiver side, the ground node uses TDMA-like communication slots with guard intervals between slots. The communication between the mobile nodes is not synchronized. 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.

In-Band: To extend the life of sensing nodes, **AWD-MAC** [64] also utilizes the receiver-initiated scheme but employees a single channel for communication. Different from the traditional receiver-initiated cycled receiver (RICER) where only one common broadcast beacon is sent, AWD-MAC sends a set of wake-up beacons in sequence to wake-up multiple neighbors. AWD-MAC also 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 still occur during the neighbor discovery phase when AWD-MAC sends a broadcast beacon to detect new nodes.

D. Bi-directional MAC Protocols

One of the advantages of using WuR technology is that it can be utilized for bi-directional wake-up procedures. 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. There are few existing MAC protocols, which apply this schema using existing wakeup radios to WBAN such as VLPM [123], WhMAC [72], [73], On-Demand MAC [3], [4], and GWR-MAC [54], [55]. 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 to, 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.

Chronologically, Guo et al. [41] proposed one of the earliest protocols to show the benefit of bi-directional wake-up using WuRxs over traditional radios with duty cycling MAC. The receiver assigns the nodes with different channels by encoding channel information in the wake-up beacon called *channel 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. Authors through the simulation of their protocol in broadcast mode showed that power reduction of 10∼100 times can be achieved with WuRxs compared to duty cycled based radios.

An extension to STEM [104], a bi-directional communication is proposed in [79]. 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. The proposed idea is compared to STEM and the simulations show significant reduction of the delivery latency and energy. However, all the nodes share the same wake-up channel without specific node addressing, which can trigger all the nodes. A similar protocol has also been proposed in [56] for detecting malicious nodes using passive WuRxs.

VII. Routing Protocols utilizing WuRs

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. Nevertheless, several WuR based routing protocols have been developed for flooding, single-hop and multi-hop data collection and dissemination. Table IV summarizes the various WuR based routing protocols.

A. Routing Only Protocols

In [114], Stathopoulos et al. 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 network. Latency is the main issue here as path discovery using low data rate network can be time-consuming. Since the topology controller is centralized this can lead to a single point of failure, crippling the entire network.

To achieve reliable end-to-end data delivery, a load-balancing, and optimized data flow communication routing tree is proposed by Vodel et al. [126]. **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.

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, have been recently proposed by Petrioli et al. [93]. 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.

Recently, the authors in [39] have extended the Collection Tree Protocol (CTP), a *de facto* standard for data collection in WSN to work with nodes coupled with WuRs [10]. **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.

B. Cross-Layer Protocols

The majority of the communication protocols discussed so far are individually developed for each separate layers of the stack i.e, MAC, Network, Transport, and Physical. Although these protocols may exhibit good performance in terms of the metrics related to each of these single layers, they are not jointly optimized in order to maximize the overall network performance while reducing the energy expenditure. Therefore, Cross-layer design presents a promising alternative in streamlining communication between layers and providing the response based on a complete view of the stack such that system utility and energy efficiency is maximized.

Out-of-Band: A cross-layer energy aware routing (**EAR**) protocol using WuRs have been proposed by Shah et al. [105] that 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

TABLE IV: WAKE-UP RADIO BASED ROUTING PROTOCOL DESIGNS

Protocol	Year	Path Request	Hardware	Addressing	Topology	Implementation
EAR [105]	2002	Source	Symmetric	ID-based	Multi-hop	Simulation
Stathopoulos et al. [114]	2007	Source	Symmetric	ID-based	Centralized	Testbed
WRTA [126]	2012	Sink	Symmetric	ID-Based	Multi-hop	Testbed
FLOOD-WUP [93]	2014	Sink	Symmetric	ID-Based	Multi-hop	Simulation
CL-RW [18]	2014	Source	Symmetric	ID-Based	Multi-hop	Testbed
ALBA-WUR [113]	2015	Source	Symmetric	ID-Based	Multi-hop	Simulation
ZIPPY [117]	2015	Sink	Symmetric	ID-Based	Multi-hop	Testbed
CTP-WUR [10]	2016	Source	Symmetric	ID-Based	Multi-hop	Simulation

regarding routing of packets. The energy level information is used as a weight factor when routing the data, avoiding the paths with less remaining 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.

Another opportunistic cross-layer MAC protocol leveraging WuRxs for selecting the best receiver among its neighboring nodes using energy as a metric is presented in OPWUM [7]. 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**) [112] 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 also does not investigate the importance of system delay and is tested in simulations only.

Spenza et al. [113] 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 [92]. 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.

A practical application of ultra-low power sub-GHz WuR is presented by Sutton et al. [117]. **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.

In-Band*:* Cross-layer Radio Wake (**CL-RW**) [18] 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 [2] and the experiments show significant reduction in the power consumption.

VIII. KEY APPLICATION AREAS

With the understanding of the ultra-low power WuR built in the previous sections, we now briefly discuss multiple application scenarios that can take advantage of it. Table V 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 [19]. As an example of the latter, a glucose

TABLE V: WAKE-UP RADIO BASED APPLICATION REQUIREMENTS

Applications	**Range**	**Lifetime**	**Mode of Data Collection**	**Network Type**	**Network Density**	**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
Requirement Importance	- Low	- - Very low	+ High	++ Very high				

level monitor requires less than 1 kbps while an ECG can reach 192 kbps [19]. 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 [115]. Notably, the short range is not an issue for these applications [90], 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 [125]. With low sensitivity demand, energy efficient WuRs can be implemented as a simple star topology with the number of nodes ranging from two to ten is enough.

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 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 [30]. 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) [85]. The feasibility of utilizing WuRs for data aggregation and for opportunistic networking in a smart city scenario has been demonstrated in [89].

Infrastructure monitoring is also possible by using WuRs in a multi-hop manner [59]. 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.

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 [38] 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 [20], 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.

IX. CONCLUSIONS

Our survey clearly identifies growing interests across many facets of the design space of wake-up receivers. Available hardware is expanding, with improvements in range, sensitivity and consumption. Protocol stacks are emerging to exploit the primary properties of this new 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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