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An Overview on Low Energy Wake-up Radio Technology: Active and Passive Circuits Associated with MAC and Routing Protocols

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ABSTRACT

The Internet of Things (IoT) is currently used in many wireless sensor network (WSN) applications. Conventionally, the WSN's energy consumption is considered as one of the prime concerns. The energy consumption is mostly due to the sensing, data processing, communications and other wasted energies such as idle listening, collisions and overhearing. These sensor nodes are regularly powered by an external power source and consequently have a shorter lifetime. Fortunately, different approaches for wireless energy harvesting (WEH) have been improved. Thus, wake-up radio (WuR) becomes a remedy for WEH which provides active, passive and semi-passive circuits consumption and other protocols. For instance, the most used, convincing and productive go to passive WuR which can significantly increase the network lifetime in a sensor network (SN) by decreasing unnecessary idle listening. Eventually, this paper proposes a state of the art in active, semi-passive, centering more on passive WuR and covers the applications areas. Then, an overview of WuR related to physical, medium access control (MAC) and routing layers. Lastly, the paper accentuates the potential research opportunities for wake-up technology for future IoT applications.

1. Introduction

The Internet of Things (IoT) technology provides a new boundary that considers network among smart physical objects or “Things” and their processing capabilities [1–3].

This latter is looking forward to present a bright solution to users. It is a model of wireless evolution, where smart detectors and devices transmit and receive data by integrating numerous protocols functioning as radio frequency identification RFID and WSN [4]. Generally, these devices are battery-powered with limited dimensions, capacity and thus have a short lifetime requiring careful power management. IoT systems offer recognizing, collecting, saving, operating and transferring of data from virtual online sensors and real time sensors [5, 6]. The utmost complication confronted by IoT devices is the restricted energy source. The accessibility of the power in the sensor nodes is necessary to permit reliable communication [7]. So it creates power management and energy efficacy critical for advanced IoT applications [8].

A WSN contains a group of sensor nodes coordinated into a collaborative network. Every sensor node consists of various sorts of memory, processing units, collected data.

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It may involve few sensors to obtain data from the environment, a power source (batteries or energy harvesting components) and a wireless transceiver (a component in which consists of a receiver and a transmitter) [9]. A sensor is, therefore, an energy-restricted device that supports the abilities of detecting and data processing, storing and transmission [10].

The WSNs can improve many facets of our life. Indeed, they are widely used today in various applications such as drones [11], green IoT [12–14], factory automation [15, 16], healthcare applications [17–19], smart city [2, 20], monitoring environment [21] and security systems [22]. As we know, the WSN sensors are autonomously and spatially distributed. Hence, the related problems in this kind of network include consumed energy and latency [10].

The networking applications especially WSNs, offer huge deployments of battery-powered devices that are connected to communicate wirelessly [3]. For that reason, the reduction of consumed power in battery-powered WSN nodes is a critical confrontation [23]. As said previously, radio frequency (RF) transceiver is the predominant energy consumer in a WSN node and most of the research has been selected for protocols and designs that decrease the power consumption [24, 25].

Among the consumed energy sources, the most significant are radio operations transmission and listening [23]. Idle listening is by definition duration of time during which the transceiver is functional without transmission or receiving of data by a sensor. From time to time, it does listen for the incoming signal from the neighbouring sensors (overhear) [24]. One of the proposed solutions was the duty cy-

cling and was utilized for addressing the idle listening challenges. It reduces the consumed energy due to overhearing and idle listening in the sensor nodes [8, 26].

To reduce the consumed energy, it has nodes operating in accordance with the set duty cycles. The radio is remained in a "sleep" state until it is fitfully turned into "active" state through its internal synchronization clock for data communication. Consequently, nodes switch between a "dormant" and an "active" state. In the "dormant" state their radio is turned OFF as well as the energy intensive processing and communication systems. An "active" state is one in which their radio is turned ON, allowing the communication [3], [27].

Hence, the energy is stored when a node is in a "dormant" state. It thus absorbs orders of magnitude less energy than in an "active" state case. The duty cycling has a crucial challenge in waking-up the nodes on time when packets have been transmitted to it, i.e., they are received at the nodes' end [28]. In the sleep period case, it is planned to be longer than the active period, extra energy is kept [29]. However, there is a high prospect of lost packet throughout sleep time and network latency because of the expanded waiting time. Moreover, it becomes at the cost of a remarkable rise in the data transportation latency [3]. In reality, the latency, in various applications, produced by duty cycling is undesirable [30]. So passive WuR is considered as a real solution.

Besides passive and semi-passive WuR types, two types of WuR are under development by using external power such as active and semi-active WuR. First, an activate WuR the sensor node that orders a power supply for the wake-up circuit [8]. For semi-active WuRs, a couple of units of the receiver demands an external continuous source while the RF front-end sustains passive [31]. The passive wake-up receiver (WuRx) is energy harvested powered from the wake-up transmitter (WuTx). So a passive WuR benefits of not employing any energy supply from the battery [32]. Briefly, this paragraph will be widely studied in the rest of the article. Also, it holds one of the currently unfolding solutions which is low-power WuR for next generation green IoT systems. It has driven IEEE 802.11 Task Group to set up the employment of WuRs since 2017 [33].

In this paper, we would like to accentuate on many problems that WuR is facing in order to propose solutions that will reduce the consumed energy in the current radio circuits. Thus, the plan of the rest of the paper is organized as follows. In section 2, we suggest the knowledge of active, passive and semi-passive WuR systems as well as architectures of WuRs circuits and each of their technologies are given in order.

Furthermore, in section 3, we present various MAC protocols used for the passive WuR technologies to control low-power networking. Also, we set a timeline of diverse MAC protocols evolution, followed by a table to indicate the protocol references with a scheme that describes some of MAC protocols by choosing for each protocol their corresponding characteristics. Then in section 4, routing protocols are proposed to solve one of the challenges of sensors that appear in the base station range and to find the best way to deliver

the message information. In this paper, we also propose the routing protocol methodology as the MAC protocol in section 3.

In section 5, we create a table of comparison representing a classification of wake up devices based on mobility, data rate, sensitivity range, energy consumption and other features.

In section 6, we have listed the most popular application areas where these combined operated structures have been developed. The field instances chosen are healthcare applications, environmental applications such as smartCity, smart wildlife monitoring, smartGate, smart building, security systems, indoor localization, WSN for an urban area, green IoT, etc. Finally, section 7 contains a summary of all the work in the article and concludes with some ideas for further investigation.

2. Physical architecture of WuR circuits

This section gives out dimensions of WuR, physical architectures of WuR circuits and each of these technologies are illustrated in the tables below. Different technologies are used to obtain active, passive and semi-passive circuit based on the usage of micro-controller and dedicated circuit.

2.1. Measurements for Classifying a WuR

The classification of the WuR is defined by the recognition of four considerable parameters such as power source, addressing capability, channels, communication medium and the reference numbers. Therefore, Table 1 addresses each major parameters, starting with the power source, as it has the most affected influence on the efficiency of the system. Subsequently, we are going to expand the description of the power sources regarding their technologies and architectures.

In Table 1, we present the literature and classify the different power sources WuR which are an extension of article [8] since the last years, and few characteristics are added based on addressing method distribution, topology transmission in a wireless network as single-hop or multi-hop.

For the unicast, the wake-up signal (WuS) can hold a bit sequence, commonly 8 to 16 bits, for particular node addressing. In that way, it raises the packet dimension, but decreases overall consumed system energy. The WuRx examines if the signal was purposed or not, after receiving the WuS. In this case, it activates the sleeping node dedicated to receiving data. We consider that the energy is used to decode a wake-up packet. Moreover, the length of the address encoding has an impact on the performance. The Trading-off among the length of the WuS and the energy savings has shown that the energy employed to transmit the selected WuS pays off if nodes are truly woken up. It means that the energy needed to transfer the WuS is excessively greater than the energy waste throughout false wake-up [8, 72]

While for the broadcast, the whole neighbourhood of nodes is receiving the WuS, the scheme is directly leading to a broadcast. This latter benefits by reducing the data latency.

Table 1

Table showing the hardware design space of WuR.

Power	Addressing	Communication	Reference
Passive	Unicast	Out-of-Band	[26, 34–36]
		Indifferent	[37, 38]
Semi-Passive	Broadcast	Indifferent	[39]
		Out-of-Band	[40–42]
	Unicast	In-Band	[43–45]
		Indifferent	[25, 46–49]
Active	Broadcast	In-Band	[50]
		Out-of-Band	[51–55]
	Unicast	In-Band	[56–63]
		Indifferent	[64–67]
	Broadcast	In-Band	[68]
		Indifferent	[42, 69–71]

Nevertheless, this is highly expensive in total consumed system power due to all the waking up neighbouring nodes [31].

On the other hand, besides WuR addressing types, we will show the usage of distinct communication by WuR transceiver for WuS transference and data. The selected propagation channel is related to the device and the application with which the WuR is connected.

- **Communication In-Band:** The principal node transceiver and the WuR apply for the identical frequency band and can divide the same antenna. This strategy is low-priced, so there is no need for another antenna.
- **Communication Out-of-Band:** Opposite to the previous method, the WuRx and the master node are provided with different transceivers and frequencies. For example, in [41], the WuR prototype runs at around 860 MHz when the data radio activates at 2.4 GHz band. Employing a separated channel, such as code division systems, consists of diverse communication that allow to activate particular sleeping nodes. The advantages of employing unrelated channels is to reduce the intrusion from the nearby nodes working in the same frequency band and expand signal strength. Nevertheless, providing WuR with distinct communication is high-priced and complicated for the system design [8, 73].

In the end, we will focus on distinct communication mediums which are used for WuS transmission.

- **Medium RF-Based:** RF based WuRs, immensely low frequency (\leq kHz) to immensely high frequency ($>$ GHz), have been primarily utilized, so the scheme is mentioned to as Free Space Optics RF based wake-up [31].
- **Medium Acoustic:** Under ideal laboratory conditions, humans can detect sounds in a range between 20 Hz to 20 kHz. Acoustic based wake-up is examined. This latter does not need any particular base and the audio signals can be readily produced by any smartphone. Studies have

suggested WuR designs for WuS transmission based on sound wave [74–76].

- **Medium Laser On Air (LOA):** This communication medium optical has been used additionally for indoor sensor networks [77, 78]. For instance, studies have proposed free space optics (FSO) for transmitting WuS [77].

In addition, the WuR channel can be categorized in the two fundamental wake-up communication network forms: the single hop and the multi-hop wake-up networks.

- **Single hop network:** In a sensor network (SN) structure, the WuS is transmitted by the main or simple WuR to a nearby node. Then its WuRx will assemble, save and collect sufficient energy from the transmitted signal in order to activate the main radio by a wake-up interruption. For a single hop network, this latter is therefore activated to improve the demanded communication task. Afterwards, the WuR will instantly reinstate to 'sleep' mode [79].
- **Multi-hop network:** However, for a multi-hop network, the WuR will resend the WuS to a nearby node before returning to 'sleep' mode [79].

Eventually, the previous Table 1 helps to the convenient WuR technologies which could face the system restrictions. For the rest of article, the part which is related to the table, we will show the architecture followed by their diverse technologies and furthermore.

2.2. Active Wake-up Radio

The WuR always comes as one of the solutions to solve the overhearing in a network system and the idle listening in the sensor node. This section introduces active WuRs that prefer an external continuous source in order to collect a packet. Then, we will divide this section into four different classifications: the various technologies of active WuR, shown in Table 2, utilized to achieve the prototype, and the other three characteristics, presented in Table 3, concern band frequencies utilisation, techniques or process signal and modulation applied. In the rest of this section, we abandon the RFID and focus on WSN because we concern on ranges starting from a few meters to kilometers.

Looking back to Table 2 concerning the WuR categorization based on technology, the design technology and its implementation are definitively related to the most power consumption of the WuR. Generally, digital circuitry are made from the chip invention technology for example BiCMOS and CMOS and analog circuitry from off-the-shelf discrete elements which their usage, with ICs packages, has permitted designers to clarify and raise WuRs prototyping with reliability, cost and low power consumption [31]. Besides surface mounted device (SMD) consists of many electrical components, such as CMOS and BiCMOS, is a process in which these components are mounted precisely onto the surface of a PCB.

Some of the illustrations of WuR technologies: for instance, concerning the discrete technology, in [60], the authors Petrioli et al. proposed a WuRx applying entirely discrete elements in which hold up four diverse channels, hence

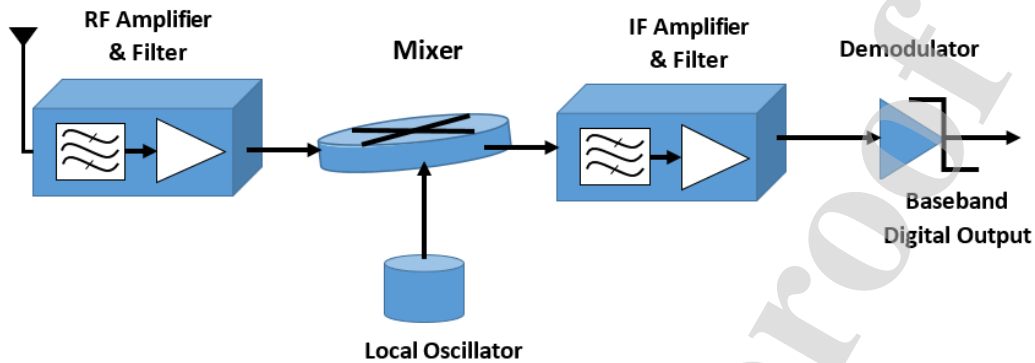


Figure. 1: Block diagram of Heterodyne WuRx.

Table 2

Active wake-up radio categorization based on technology.

Technology	Reference
Discrete component	[28, 51, 52, 56] [59–61, 80]
SMD	[55, 57, 58, 81–86]

authorizing node addressing. The receiver front-end includes the antenna, three power splitters and low noise amplifier along with the filter bank. The WuRx sensitivity is -83 dBm, whereas its consumed power is around 1620 μ W. The communication range does not exceed 120 m. Nevertheless, the proposed design also has a greater power demands comparing to other WuRxs.

For the past years, the consumed power of CMOS devices has markedly decreased in order to allow for the inventors and scientists to sketch ultra-low power circuits. Progressively, developing ultra-low power radios first came up with the PicoRadio project. This project suggested a CMOS based node design. This proposition served as a WuR and as a data radio with data rate higher than 100 kbps. Besides, the same project has a 10 m range and absorbs 400 μ W from a supply voltage of 1V [81]. Figure 1 shows one among many proposed CMOS based prototypes in which have selected a heterodyne technique. It is a mechanism to transform an arriving high frequency RF signal into a lower frequency through combining at least two signals or more.

In [55] Pletcher et al. considered a 1.9 GHz WuRx chip consuming 65 μ W from a 0.5 V supply in an active state. The receiver data rate is 40 kbps as well as the sensitivity is around -50 dBm, through OOK for WuS modulation. The architecture was also ameliorated in [83] across an “uncertain-IF” design in order to decrease the consumed power to 52 μ W with improved data rate and sensitivity of 100 kbps and -72 dBm, respectively.

An additional 2.4 GHz adopted by heterodyne WuRx

Table 3

WuR classification based on frequency employment, address decoding and various WuS modulation approaches.

WuR categorization	Classification	Reference
Band	sub-GHz	[31, 52, 54, 87]
	2.4 GHz	[31, 57, 64, 82, 85]
	5 GHz	[70]
	60 GHz	[65]
	Others	[62, 71, 81]
Technique	MCU	[51, 52, 56, 61, 62]
	Correlator	[85, 88–91]
	AS3930	[28, 59, 63, 80, 84]
Modulation	Others	[58, 60, 68, 92]
	OOK	[60, 71, 87, 93, 94]
	ASK	[51, 64, 68, 70]
	FSK	[69, 90, 93]
	Others	[57]

was advanced in [57]. This WuRx front-end’s major building blocks are composed of a matching network, an antenna and a LO generator for minimizing the frequency. The IF signal is thus amplified through many frequencies IF amplifier and then lessened to baseband using a full-wave rectifier. It determines that WuRxs can achieve sensitivities as high as -82 dBm while only dissipating 830 pJ/bit.

After explanation of some of active WuR technologies, we move on in our study of active WuRs to explain the other

categories such as operating frequencies which have been used in many bands, address decoding and WuS modulation techniques.

- **Operating Frequency:** Another problem takes place when it comes to transmitting WuR frequency. In the case of using incompatible frequencies for the WuR and the main data transceiver, each must require a distinct antenna for detecting signal and distinct matching networks. Further, choosing an operating frequency for WuRx is disapproving because it decides the dimension of the antenna and the system range.

One of the operating frequency examples is presented by Spenza et al. which is sub-GHz WuRx in [52] consumes 1.276 μW in listening mode. The receiver, using OOK modulation, consists of four prime slices: a matching network, a detection envelope along with a preamble tester and a comparator. The sub-GHz WuRx has -55 dBm sensitivity and 100 kbps data rate, while realizing 45 m of the largest wake-up range. Further, this architecture is enhanced in [87], which uses 0.152 μW consumed power in the listening mode at sensitivity of 32 dBm. This specific WuRx has accomplished a fascinating communication range of more than 50 m and provides 10 kbps data rate.

Lately, in [62], Juha et al suggested, for human body communications, a 28 MHz always ON WuR architecture adopted by super-regenerative. In order to accomplish great sensitivity and low consumed energy, the WuR applies loose synchronization while managing at 1.25 kbps, consumes 40 μW and achieves -97 dBm sensitivity.

- **Address Decoding:** Later, including node address decoding ability to the WuRx needs supplementary elements at the RF back-end. A low power micro controller unit (MCU) or correlator is usually implemented for decoding. Nevertheless, it is followed by trade-offs.

To confirm what we said previously, in [56], authors propose PIC12F683 MCU integrated in order to expose and decode a WuS and inform AT-mega128L processor of the essential node by an interrupt. In [56], the WuRx consumed power rises from 171 μW in listening mode to 819 μW at 3V. This prototype, using OOK modulation, communicate up to 2 m with -51 m receiver sensitivity. As for another prototype in [61], with the same communication range, has 0.69 μW of low power consumption in 868 MHz band.

Furthermore, in [88], Hambeck et al. depicted a WuRx prototype using a 64-bit combined signal correlator for address matching. However, the design contains a receiver sensitivity of -70 dBm, at 868 MHz, and a regular free-space radio link distance until 304 m at 6.4 dBm of transmission power. In that case, the WuRx dissolves barely 2.4 μW at 1 V.

For the last address decoding technique, in [59], WuRx AS3933, for IEEE 802.11, authorized wireless access points that were proposed by Oller et al. This model has -52 dBm WuRx sensitivity and the overall power consumption is around 24 μW in active state.

Other address decoding techniques, article [68] has simulated a special Bloom filter adopted by wake-up mechanism for WuRxs. For a bit rate of 40 kbps, the receiver's listening consumed power is 12.4 μW . In an active state, the circuit used 368 μW at 1.8 V.

- **WuS Modulation Approach:** To realize the demand of ultralow power consumption, diverse modulation methods, such as OOK, FSK or ASK, have been used for the WuSs.

Conventionally, these popular modulation classes are considered in the presence of an interfering signal. OOK modulation has a particular case of ASK modulation where no carrier is given when it indicates a binary zero, hence conserving power. For FSK modulation, it usually performs better in the existence of any interfering signals. Nevertheless, this latter is more expensive and complex in implementation. Lastly, ASK is an amplitude modulation type which represents digital data as variability in the amplitude of a carrier wave. Therefore, ASK modulation is a substitute to OOK and FSK modulations because it provides the immunity of interfering signals more than OOK and is easier to implement at a lower cost than FSK modulation [95].

As it can be seen in Table 3, OOK is one of the most used modulation technique used to modulate RF signal before receiving by the WuRx. In OOK modulation case, the source node sends an immense amplitude transporter when the presence of a carrier for a specific duration represents a binary '1' and a binary '0' if nothing is sent, i.e., the transmitter became inactive. This way has authorized OOK hardware executions to be relatively straightforward as their low performance cost for battery-operated cases. In [87], the WuRx consumes 1.2 μW with -55 dBm of sensitivity at 10 kbps data rate to demodulate a 868 MHz OOK signal.

When it comes to ASK, a popular modulation scheme, it is employed by WuR hardware specialists. Related to OOK, the ASK data is further transferred through binaries '1's or '0's. Nevertheless, the transmitter sends short amplitude transporter in its uncomplicated form instead of remaining the transmitter off when designating bit '0'.

Ultimately, FSK demodulation, WuRxs are adapted on frequency distinction design. In [69], the WuRx absorbs 2700 μW to demodulate a 915 MHz FSK signal. The receiver sensitivity is around -90 dBm at 45 kbps of data rate.

Comparing these three modulations, ASK offers a lower cost than FSK and a greater noise immunity comparing to OOK which has lower power consumption request than ASK based WuRxs.

2.3. Semi-Passive Wake-up Radio

The weight of the suggested architecture approaches semi-passive in order to control the nano-Watt power range. Thus, a few receiver front-end modules are powered by an external continuous source while the other modules are completely passive. The advantage of the passive circuitry usage is that

Table 4
Semi-Passive wake-up radio categorization based on technology.

Technology	Reference
Discrete component	[26, 36, 41, 42] [44, 45, 47]
SMD	[25, 43, 46] [50, 97–104]

permits decreasing the power consumption. The weakness of this circuitry is the limited communication range and the reduction of receiver sensitivities. The most usual procedure, for the radio front-end, is to build a detection envelope employing passive elements, for example Schottky diodes [96], or MOSFETs [87], along with the active elements such as comparators or correlators. Furthermore, we will show WuR models that use such design.

In Table 4, we showed some instances of semi-passive WuR classification based on technology. One of these technologies, was proposed by article [41] which illustrates a radio triggered wake-up circuit utilized its specific MCU for address decoding. The main buildings blocks contain an impedance matching network, a digital comparator connected to the main MCU and a voltage multiplier. The matching network uses discrete components such as inductors and capacitors. Furthermore, the MCU shows the low-to-high conversions and the period between the pulse interval encoding (PIE) signal to achieve the data decoding. If the wake-up packet is not directed to the node, it returns to the 'dormant' state. The WuRx only utilizes 2.628 μW in listening mode and the MCU absorbs about 1000 μW if it converts from dormant to active state for address decoding.

Moreover, Ammar et al. [26] presented a 868 MHz semi-passive WuRx that implements Flip Flops for address decoding and dissolves only 13 μW . Nevertheless, this latter architecture is estimated by simulations.

Gamm et al. [44] has also suggested the original in-band sub-Carrier modulation WuRx system adopted by AS3932 shown in Figure 2. In the wake-up state, the WuS is headed to the AS3932 WuRx, which pulls out the 125 kHz signal from the 868 MHz WuS, for the envelope and address decoding after impedance matching using OOK demodulation. When the address is suitable, the prime node is triggered. Subsequently, an antenna is employed to bypass the WuRx through the main transceiver. For the main radio, this is equally employed as a WuTx to produce the WuS. The WuRx circuitry is charged with 3 V of continuous source and has 7.8 μW of active consumed power.

Ultimately, the CMOS technology is well proposed by Roberts et al. [25], Huang et al. [102] for multi-band WuRs, Oh et al. [103] for tri-band 116 nW WuRx with 31-bit Correlator, Le-Huy et al. [43] and other authors as well. Roberts et al. [25] presented the highest energy efficient semi-passive circuit in which the energy is collected from the RF signal and the received voltage is thus enhanced through resonant tank before contributed to the circuit active part. Thus, this

Table 5
Passive wake-up radio categorization based on technology.

Technology	Reference
Discrete component	[105]
SMD	[7, 24, 34] [38, 39, 101]

915 MHz band WuRx has 1.2 m of communication range at 0 dBm transmitted power.

Article [102] suggested a radio triggered WuRx capable to select the range of frequencies between 915 MHz and 2.4 GHz band. This latter absorbs 51 μW for 100 kbps OOK modulation along with -75 dBm of receiver sensitivity in the 915 MHz band.

Recently, in [103], the chip contains a 30-stage passive rectifier to convert the RF signal into baseband and an input matching network to boost the arriving WuS. The WuRx front end manages in the 402 MHz MICS band and the 915 MHz ISM band with sensitivities of -45.5 dBm and -43.4 dBm, respectively.

2.4. Passive Wake-up Radio

As we have explained briefly before, passive WuRs contain limited ranges than the active WuRs, usually by a few meters. Also, the measurement of receiver sensitivity depends on the performance of the receiver and is specified as the power of the weakest signal. The receiver sensitivity is an important parameter as well in WuR design in which greater sensitivities occur in longer wake-up range. In Table 5, we propose technologies that collect and power the wake-up circuitry from the RF signal. Hence, passive WuRxs benefit of saving energy in the node battery thus we have a safe intended energy.

In 2005, Gu and Stankovic proposed in [105] a prime proof-of-concept based on passive WuRx architecture at 433 MHz. The radio signals give power to this latter, capable to activate a wake-up interrupt in case the energy has been collected and saved on the capacitor. The design, evaluated through SPICE© circuit simulations, proposes a charge pump approach containing zero-bias Schottky diodes and capacitors. Besides, it allows the addressing ability by sending the WuS at various frequencies to reach around 3 m of operating range. Furthermore, the WuRx consumed power, in idle mode, is 145 μW .

For passive WuRxs, based on CMOS technology, they are noted in [7], [101], [39]. So in [34], there is a proposition of one more battery-less WuRx at 900 MHz band. This CMOS chip contains an RF front-end and a digital baseband. Together with the radio, building blocks consist of a voltage multiplier, a voltage controller, modulator and demodulator circuits along with a ring oscillator. Employing ASK modulation scheme, the prototype accomplished -17 dBm of sensitivity range with 2.64 μW consumed power.

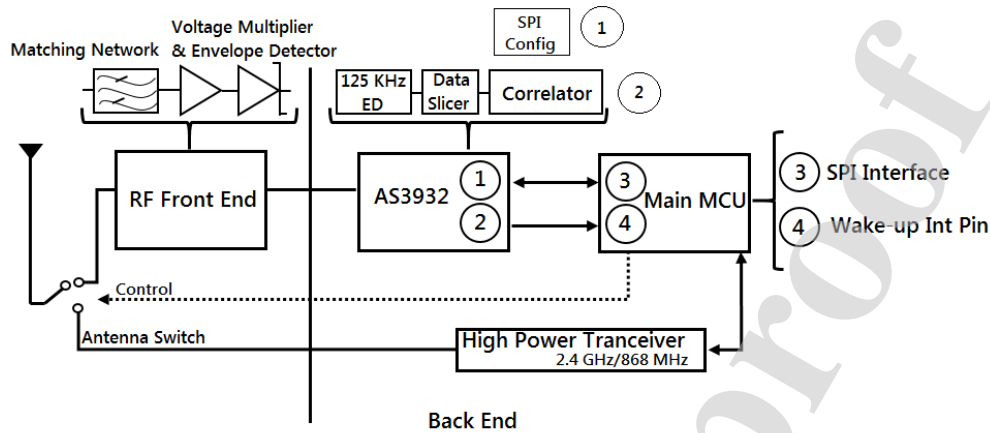


Figure. 2: WuRx prototype using Austria Micro Systems AS393x WuRx.

Also, article [24] suggested a passive 868 MHz WuRx front-end. The block contains an antenna, matching network, data slicer and voltage multiplier along with an RF-to-DC converter in order to create the OOK WuS envelope. In addition, Zgaren et al. in [38] enhanced the technology of article [24], previously mentioned, and suggested a passive WuRx model for implementable components working in 902-925 MHz band. The two prototypes were done using a simulator.

Summarily, CMOS technology is more branched for implementing passive WuRxs by reason of its short consumed power. However, RFID has been employed since it supplies energy harvesting (EH) abilities, therefore, decreasing the performance and the execution period.

Afterwards, the hardware part necessitates to be connected with the WuR to better perform this functionality which will be elucidated in the following. As explained earlier, passive WuRs always need power to manage, which can be accomplished through collecting energy from the approaching RF WuS. Therefore, hardware must be adjoined at the WuR to obey this task. Accordingly, this makes changes in complexity and size of the circuit. However, a delay in the main WuR is caused by the energy harvesting process owing to the time required to collect enough energy. In that case, this allows to increase the latency and decreases throughput in the node which influences the overall network improvement.

Generally, consumed power, sensitivity and wake-up range are principal characteristics for a productive passive WuR performance, the trade-off among these features are considerably required throughout the circuit architecture [8].

Many disadvantages are considered for the passive WuRs such as limited ranges than the active WuRs, regularly by a few meters. This latter is followed with a limited sensitivity as compared to the active WuR. Besides, if the WuS is transmitted by the main radio, in that case, the sender is obliged

to modulate the WuS and send it normally for seconds which is considered a long period, in order to be detected at the receiving point. So this is also considered as an extra work for the transmitter in which more power is consumed.

In Figure 3, we will show a common sensor node followed by a passive WuR which contains eight essential chips: micro controller, power management, memory unit, antenna, ADC converter, sensor node, EH wake-up radio and main RF transceiver [8].

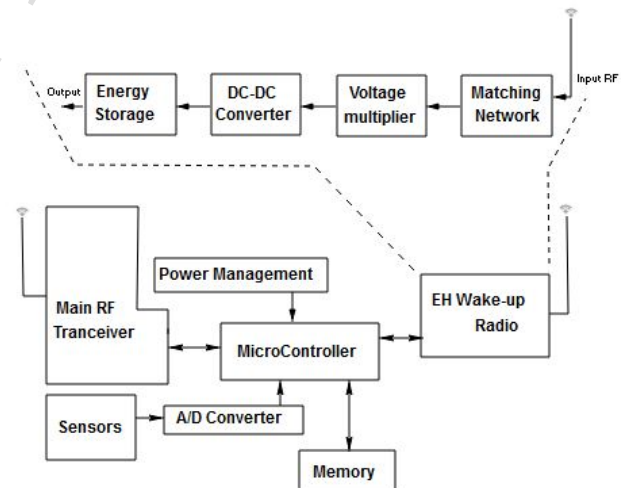


Figure. 3: Sensor node with passive WuR.

From Figure 3, the antenna, that received the WuS, progressed along the energy harvesting process. The MCU chip is activated by the harvested power. Then, this latter transmits an interrupt signal to the main WuR in order to trade data messages. The EH wake-up radio block, that only con-

verts from a sleep mode to an active mode after obtaining an external RF signal to wake-up the radio, contains four units: matching network, voltage multiplier, energy storage then the antenna as the RF input, which will be elucidated down below.

In addition, this following is aimed at proposing a simple approach, through schemes, circuits or analytical description of each of EH WuR units in order to estimate and recognize the levels of components shown in Figures 4-8 such as capacitors, inductors, diodes, switches, etc.

- **Antenna:** The passive WuR's antenna converts the received RF signal into an electrical signal through electromagnetic induction, considered as a matching network unit. As it is known, the antenna collects diverse frequency bands so the antenna can assemble single [106], dual [107], triple [108] or broad [109] band and others depending on the frequency bands in whatever place the antenna controls.
- **Matching Network:** The reason that matching network includes passive elements such as capacitors and inductors, connected either in series or parallel (see Figure 4), is to avoid noise in the circuit. Also it is desirable to avoid the wastage of power. The purpose of using matching network is predominant due to the matching among the antenna impedance and the input of the rectifier diode. Hence, we call it impedance matching [110].

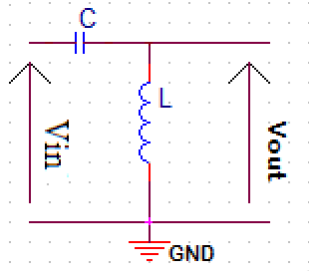


Figure. 4: Matching network circuit.

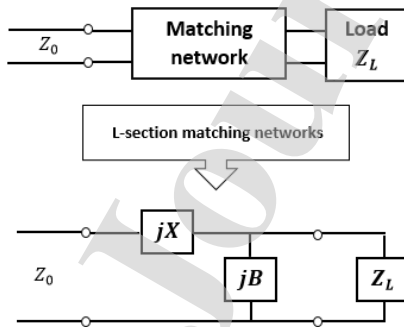


Figure. 5: L-section matching network [111].

As shown in the first part of Figure 5, the matching network's block, consists of a shunt inductor and a series capacitor, employs a fundamental configuration, the L-section, using two reactive elements to link an arbitrary load impedance to a transmission [112]. Therefore, in an L-matched network, the values of the components can be acquired through the following equations, after a long demonstration seen in the book of David M. Pozar [111].

$$X = \pm \sqrt{R_L(Z_0 - R_L) - X_L} \quad (1)$$

$$B = \pm \frac{\sqrt{(Z_0 - R_L)/R_L}}{Z_0} \quad (2)$$

where Z_L is the load impedance, R_L is the real part of the load impedance, X_L is the imaginary part of the load impedance and Z_0 is the antenna impedance (typically 50 Ω). To combine the diode with the impedance of the antenna, the values for the shunt inductor and the series capacitor are calculated from equations (1) and (2), respectively [111].

- **Voltage Multiplier:** The voltage multiplier, consists of capacitors and diodes (see Figure 6), and is connected between the energy storage and the matching network.

This unit consists of a rectifier circuit design which converts the alternating input RF signal into a higher output DC-voltage. Consequently, the passive WuR's capacitor in Figure 6 must be charged while converting the RF signal from the matching network unit to DC through a rectifier circuit mentioned before.

The voltage multiplier circuit intends to increase the output DC voltage [113]. Schottky diode [114] is the most known used diode in the circuit to rectify in passive WuR. The rectifier is thus categorized as half or full wave rectifiers based on their conducting properties and as single ended [115] or differential topology [116–119] established on their symmetry properties.

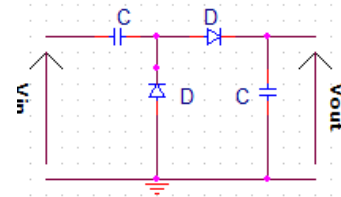


Figure. 6: Voltage multiplier circuit.

- **DC to DC Converter:** This unit is settled as an output of the voltage multiplier as well as an input of the energy storage unit. The converter can vary the DC voltage source related to the converter type and the voltage level as well [120]. So in Figure 7, the DC/DC converter unit is well known as step-up chopper. The converter increases the output voltage supplied to the capacitor and the output voltage, and the current requirements are two parameters that determine the value of the inductor. The inductor's

value is related to the current specifications and output voltage [8].

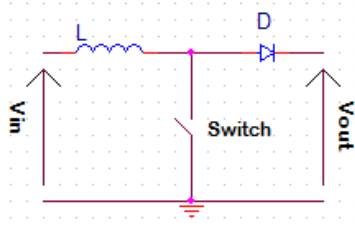


Figure 7: DC-DC converter circuit.

- Energy Storage:** In Figure 8, we show the overall circuit of energy harvesting wake-up radio where we have added a capacitor on the output of DC-DC converter to accumulate the output DC voltage. It is employed as a store source in case the energy source is insufficient. This will definitely afford endless power delivery to work on waking up the main radio then provide a permanent network operation. Moreover, some proposals on energy-storing supercapacitors [121–123] and charge pump circuits [120, 124, 125], which are a sort of DC-to-DC converter that employs capacitors for energetic charge storage manner, were given for an energy harvesting system in the matter of reducing power loss and increasing charging time.

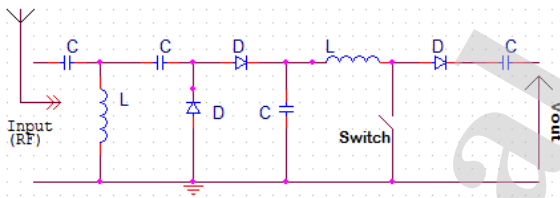


Figure 8: Energy harvesting WuR circuit.

After presenting several parts of wake-up circuit, the following describes some of MAC and routing protocols used for WuR communication.

3. MAC protocols for WuR

Most of the WuR technologies have been concerned through enhancing hardware components to accomplish greater power consumption and physical layer communication characteristics. So this section is focusing on medium access protocol by extracting diverse MAC protocol designs followed by their characteristics.

For any circuit either active or passive, the MAC protocol depends on the number of users or services for specific applications. In countless IoT applications, what interests

us the most is the energy efficiency such as external continuous source related to sensor nodes. Conventionally, duty-cycle MAC has been first approved in WSNs to decrease the consumed energy by working on permitting nodes sleep and wake-up cyclically. Some of the suggested duty-cycle [126] are PW-MAC [127], RI-MAC [128] and DC-DoRa [129] in order to lessen the suffering that comes from idle listening and overhearing. Idle listening, by definition, appears when a node listens to the channel to receive command messages while overhearing takes place when a node overhears the unexpected command messages for it [130]. Nonetheless, Wake-up radios attack the problem of idle listening and overhearing at the hardware level, however they should be associated with a MAC protocol to manipulate their use.

Figure 9 represents a timeline of the MAC protocols designs in progress, attached to Table 6 that indicates for every MAC protocol, followed by its own reference, some of its characteristics and applications. Following the accomplished works, they have been written by many authors such as Piyare et al. article [31] and article [150]. These latter focused on the evolution of MAC technologies and routing protocols from the beginning of the twenty-first century until the end of 2016. Thus, this article, so far, comes to add new MAC and routing technologies on the previous articles. Figure 10, related to the ultimate figure and table, describes some of MAC protocols followed by their characteristics: power management, channels, initiator (Bidirectional, transmitter and receiver), implementation and hardware.

In Figure 10, the first discussion demands identifying for each of pair of nodes located in the wireless channel building (see Figure 11) such as the receiver, the transmitter or bi-directional.

In the transmitter system, the node which transmits a WuS as a first step, has data to send so it begins communication, whose receipt triggers the receiver in order to convert its transceiver from a sleep state to an active state (see Figure 10 (a)). In case the transmission was successful, data is thus sent utilizing the same transceivers. Then, the Tx-ACK is transmitted from node to transmitter in case the data is completely exchanged. In the end, the nodes return into sleep mode.

Contrary to transmitter system, the WuRx is located on the transmitter side while the receiver is only limited by the node (see Figure 10 (b)). In Receiver initiated systems, the receiver starts the communication with the node, notifying receive data. Then, it is converted to receive (RX) mode in order to acquire any incoming packets. When the WuRx receives the WuS, this latter sends an interrupt signal to its transceiver which in turn is accountable for the transmission of data packet in the node. Finally, after perfectly receiving the data packet, the Tx-ACK signal is transmitted from the destination node to the sender. In the end, the nodes return to sleep mode.

Finally, for the bi-directional system, the data packet is nevertheless switched between transceivers, although the nodes, whether served to be pushed or pulled data, can launch the communication through their WuRs. This latter serves

Table 6
MAC protocols followed by reference numbers.

No.	Protocol	Abbreviation	Power Management	Channels	Topology	Initiator	Targeted Application
1	Guo et al. [131]	-	Always ON	Multiple	++	Bidirectional	Multi-hop WSN
2	STEM-B/T [132]	Sparse Technology and Energy Management Bacon messages/wake up Tone	Duty cycled	Out-of-band	++	Transmitter	Sensor networks
3	DC-DoRa [129]	Duty-Cycled Double Radio	Duty cycled	In-Band	+	Receiver	WSN
4	BATS [133]	-	Duty cycled	Out-of-band	N/A	Receiver	Tracking bats in the Wild
5	W-MAC [134]	Workload-aware MAC	Always ON	Out-of-band	++	Bidirectional	Multi-hop network
6	MAC Address Rand. [135]	-	N/A	Multiple	N/A	Transmitter	Mobile devices
7	LoRaWAN [136, 137]	Long-Range Wide-Area Network	Duty cycled	Multiple	N/A	Bidirectional	LoRaWANSim
8	CCA-WuR [130]	Clear Channel Assessment	Always ON	In-band	+	Bidirectional	Light traffic load in WSN
9	CSMA-WuR [130]	Carrier Sense Multiple Access	Always ON	In-band	+	Bidirectional	High traffic load in WSN
10	ADP-WuR [130]	Adaptive	Always ON	Multiple	+	Bidirectional	WSN
11	LoRa, SigFox and NB-IoT [138]	Long-Range, - and Narrow Band IoT	Duty cycled	Multiple	N/A	Transmitter	Smart cities & IoT
12	SD-TDMA [139]	Space-Division-Time Division Multiple Access	N/A	Multiple	++	Transmitter	*VANET
13	CB-MAC [140]	Cluster-Based MAC	N/A	Multiple	++	Bidirectional	*VANET
14	AlphaMAC [141]	-	N/A	Multiple	N/A	Transmitter	Machine learning
15	CRWN MAC [142]	Cognitive Radio Wireless Network MAC	Energy harvesting	Multiple	++	Bidirectional	Development of the wireless CRN
16	DCC-MAC [143]	Dynamic Channel Coding	Duty cycled	Out-of-band	+ / ++	Bidirectional	E-Health applications
17	QCA MAC [144]	Quantum dot Cellular Automata MAC	N/A	N/A	N/A	Transmitter	Real-time signal & image treatment
18	DCI MAC [145]	Dynamic Control channel Interval MAC	N/A	Multiple	N/A	Transmitter	*VANET
19	MU-MAC [146]	Multi-User MAC	N/A	Multiple	N/A	Bidirectional	Next-generation **WLANs
20	RoboMAC [147]	-	Energy harvesting	Multiple	++	Bidirectional	Cooperative mobile robot app
21	TDMA MAC [148]	Time Division Multiple Access MAC	N/A	Multiple	+ / ++	Bidirectional	*VANET
22	Ctrl-MAC [149]	Control-MAC	Energy harvesting	Multiple	+ / ++	Bidirectional	†WA-CPSs

Single-hop : + , Multi-hop : ++

*Vehicular Ad Hoc Network ** Wireless local area networks † Wide Area Cyber-Physical Systems

for authorizing multi-hop communication.

Later we will show the deployment of the specialized WuR hardware. Here we present options of asymmetric and symmetric paths.

In a symmetric path [151], for a multi-hop network, all

the nodes are identical and can switch either into receiver or transmitter, which all nodes are qualified with a wake-up transceiver. In a transmitter system case, the transmitter transmits a WuS to the receiver. Then, the transceivers exchange the data.

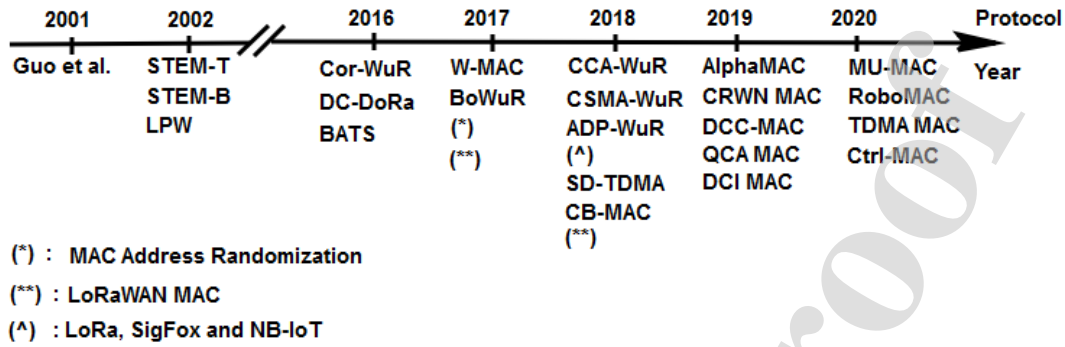


Figure. 9: Illustration of the initial standardization timeline of WuR Based on MAC protocol designs.

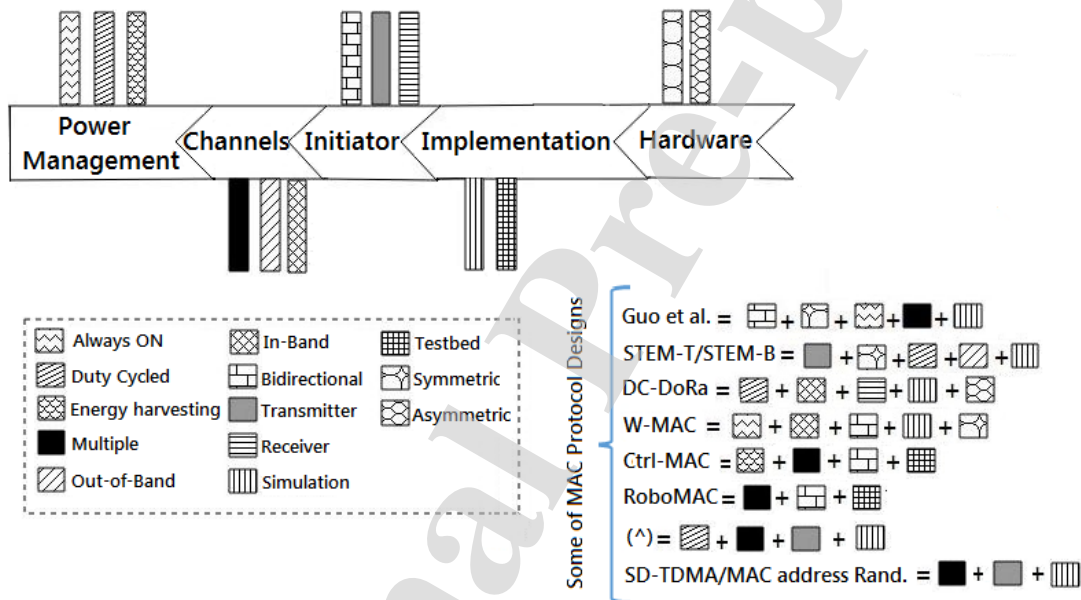


Figure. 10: Some of WuR based MAC protocol technologies.

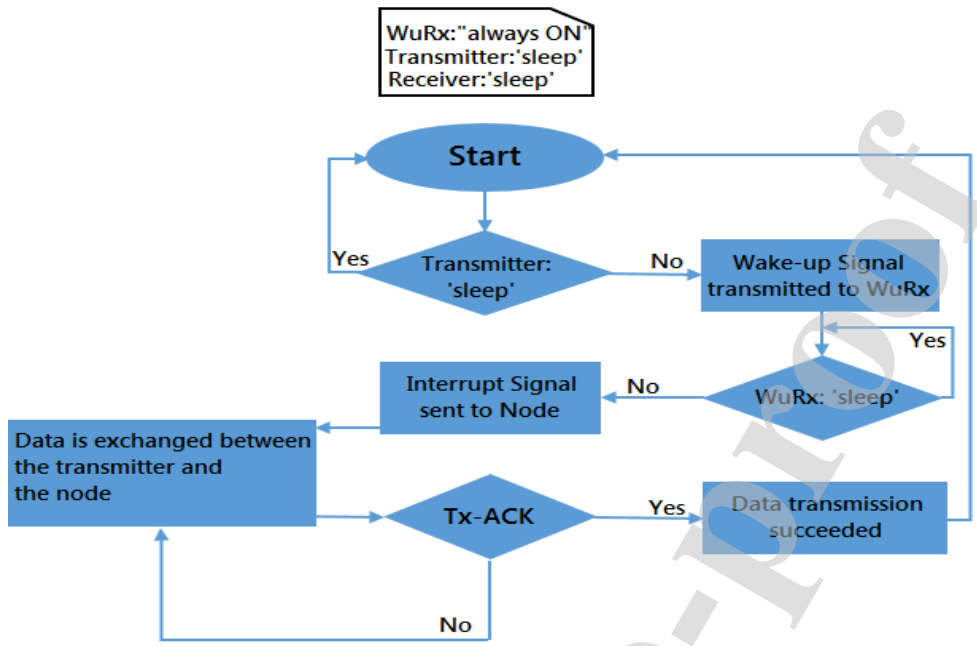
In an asymmetric path, there is only one master node that can launch a data link setup. The rest of the nodes are slaves. Consequently, since a master node can afford a larger battery, the consumed energy of the master is less valuable than the consumed energy of a node. In a powered sink case, a receiver system is utilized to reduce data from nodes side to the sink. In case of non-sink, nodes should contain a WuRx, so they can stand by in a lower consumption state, to shift into a higher consumption, if the sink is equipped to obtain their data [151].

Now, we will discuss the power usage of a WuR focusing on the time and the way with which it is activated. In Figure 10, we have mentioned three power management strategies for WuR: always-ON, energy harvesting and duty cycling.

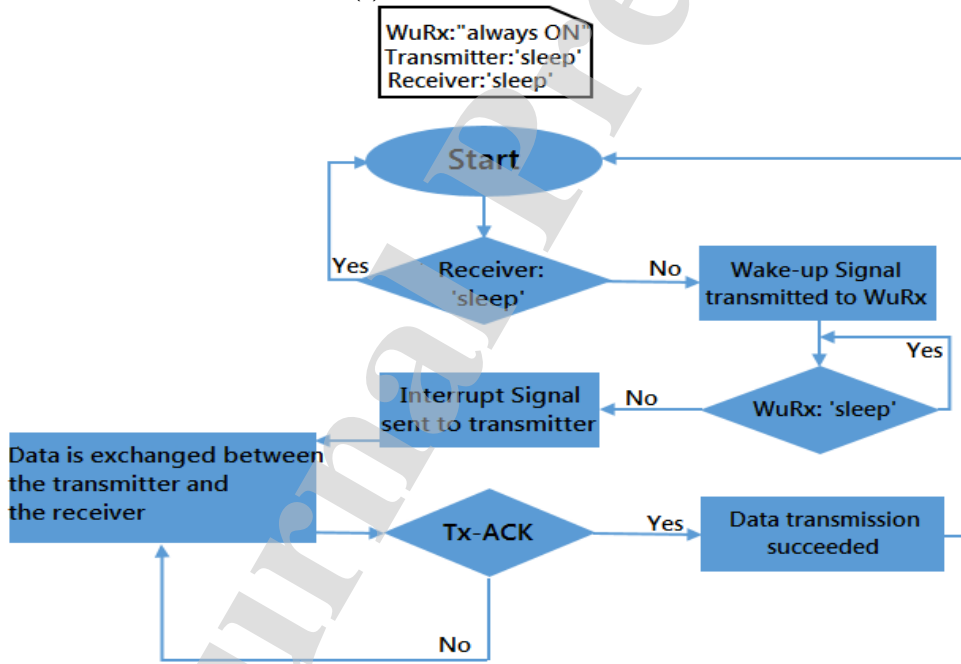
- **Always ON:** In a transmitter or receiver system areas (see

diagram 11), the power management reduces the latency. The receiver is instantly well informed of the transmitter's requirement in order to start the communication. In most cases, due to the short consumption of the WuRx technology, it can be continuously charged, waiting for a trigger signal [152, 153].

- **Duty Cycle:** Another method to decrease power consumption is to be considered as a duty cycled WuR. The WuTx transmits many of WuSs so it helps to recompense for the sleeping times of the receiver until the target WuRx obtains a wake-up acknowledgment. If it is not received, the node will resend the WuS [154], [155].
- **Energy harvesting:** In the last category of energy harvesting WuR system, the WuS harvests an adequate amount of energy. In this case, the WuRx woke up. That energy



(a) Transmitter-Initiated MAC.



(b) Receiver-Initiated MAC.

Figure. 11: Different WuR communication initiator diagrams.

that comes from the WuS is used in order to run the trigger circuitry. If there is no clue for communication, the WuRx is turned OFF [154],[155].

Now, in the rest of this section, we categorize our suggested protocols along with the scheme of Figure 10, in accordance with the communication initiator, symmetric and asymmetric hardware, diverse channels, different power man-

agement approaches and types of implementation. We also provide the categories of the protocols followed by their references in Table 6

In 2001, Guo et al. [131] is one of the initial protocols that employs Always-On WuRxs in order to reveal the advantage of bidirectional communication. The receiver specifies the nodes with distinctive data channels. The transferring node thus catches this specific information through its WuRx and converts its data radio, after operating the main node, to receiver's channel.

In broadcast mode, along with the simulation of this MAC protocol, and with Always-On WuRxs, this revealed that the reduction of consumed power goes between 10 to 100 times comparing to duty cycled WuR solutions explained previously.

Moving on to the year 2016, an adaptive duty-cycled DoRa (DC-DoRa) from J. M. Lebreton et al. [129] was, at the time, a new MAC protocol technology to eliminate the overhearing difficulty according to a duty-cycling technique adopted in WuR structure. This latter was a DoRa MAC protocol's alternative or extension which had, in turn, an overhearing problem despite the WSNs energy efficiency's improvement was significantly observed. In order to conserve a large amount of energy, this MAC technology adopted a semi-passive WuR.

Besides, most of the WuR radio MAC protocol's hardware implementations in Figure 10 are based on simulation.

In 2017, MAC address randomization was developed by J. Martin et al. [135] as a special process by which mobile devices rotate through diverse hardware addresses to avoid watchers from singling out their traffic from any neighbouring devices. Analysis, so far, demonstrates that this MAC technology policies are nevertheless not universally performed at removing privacy problems.

In addition, W-MAC was considered by R. Piyare et al. [134] for multi-hop network in which nodes can switch either to senders or receivers. This latter takes benefit of secondary always ON WuR which relates to the initial mote. Once a node owns data to be transmitted, W-MAC starts sending a wake-up beacon that consists of an aimed node address. In order to get rid of collisions, the wake-up radio work on diverse channels for wake-up beacon and data packets. Moreover, W-MAC employs simulations (shown in Figure 10) and has the capability to provide notable energy reserves without Trading-off on reliability or latency.

Progressively, D. Ghose et al. [130] suggested three WuR protocol technologies such as CCA-WuR, CSMA-WuR, and ADP-WuR respectively. It focuses on clash avoidance of wake-up calls (WuCs) and applying WuR to several traffic circumstances. Between these three technologies, CCA-WuR matches top for different fields of application in which both short delay and high energy-efficient communication are necessarily recommended. Concurrently, CSMA-WuR and ADP-WuR are advantageous when packet delivery accuracy becomes more important. However, ADP-WuR seems preferable in the matter of packet delay and consumed energy.

Another study in 2018 yield an adaptive multi-channel MAC protocol based on SD-TDMA mechanism [139] in order to enhance the usage of the time-slot distribution scheme in the vehicular ad hoc network. Furthermore, this technology decreases transmission conflicts according to user identification strategies.

More advanced MAC protocols appear in 2019 such as AlphaMAC, CRWN MAC, DCC-MAC, QCA MAC and DCI MAC (Fig.10)

A new MAC protocol challenge in automation design has been switched from human-driven design to an advanced machine-based design. So, for automating MAC protocol design, B. Pasandi et al. [141] proposed AlphaMAC framework in which it studies the automation design of structured MAC protocols. The primary results reveal that AlaphaMAC framework is capable to set optimum MAC protocols which can perform better than common protocols.

Thereafter, CRWN MAC protocol from M. Cicioglu et al. [142] was employed in this study as a suitable solution to enhance both the primary network and the wireless cognitive radio network (CRN) environment. In addition, CRWN absorbs less energy than CSMA/CA.

In machine's field, coordinated mobile robot applications allow robots to work on functions that are harder than each single robot can achieve alone. The up-to-date cooperative robot applications predict the reinforcement of low data rate networks which afford minimum energy consumption and simple WSN's integration. Hence, G. Patti et al. [147] suggests a new MAC protocol for mobile cooperating robots, RoboMAC, which manages robots incorporation with WSNs and keeps up mobility and real-time communications. Moreover, this novel protocol upholds message primacy and multi-channel communications over TDMA-MAC.

Later on, we suggest an unusual LPWA MAC protocol, Ctrl-MAC proposed by L. Bhatia et al. [149], which stabilizes the control demands of wide area cyber-physical systems accompanied by the communication restrictions and forced by Low-Power Wide Area (LPWA) communication technologies. Furthermore, the co-simulation test consequences prove that LoRaWAN and LoRaWAN++ technologies can not afford data reception warranties to the control system. So what changes Ctrl-MAC into an unique appropriate LPWA system for the long range communication is the collaboration of guarantees and low latency.

The following section describes the routing protocols. The latter is depicted with its architecture and specific characteristics. Also, the main technologies of routing protocols are presented.

4. Routing protocols for WuR

In WSNs, many of the sensor nodes are dispersed and located over a large area. Typically speaking, every sensor is allowed to transmit, receive, store, save and route data in order to transmit it to another sensor nodes or restore it to the base station [156]. The difficulty with the sensor nodes appears in the scale of the base station, so the data is transferred

Table 7

Routing protocols followed by reference numbers.

No.	Protocol	Abbreviation	Path request	Network Topology	Addressing	Class	Targeted Application
1	EAR [157]	Energy Aware Routing	Source	++	ID-Based	Cross layer	Low energy ad hocSNs
2	CTP-WUR [158]	Collection Tree Protocol Wake-Up Receiver	Source	++	ID-Based	Only routing	*GWNs
3	OPWUM [159]	Opportunistic Wake-Up MAC	Sink	++	ID-Based	Cross layer	†
4	GREENROUTES [160]	-	Sink	++	Broadcast	Cross layer	Green WSNs
5	WHARP [161]	Wake-up and HARvesting based energy-Predictive	Sink	++	Broadcast	Cross layer	*GWNs
6	T-ROME [162]	Tree Routing Protocol	Source	++	ID-Based	Cross layer	Low-power WuRx
7	La-CTP [163]	Loop-aware Collection Tree Protocol	Sink	++	Broadcast	Only routing	EH-WSN applications
8	LP-WUR [164]	Low-Power Wake-Up Receiver	Sink	++	Broadcast	Only routing	-
9	AWSN [165]	Aerial Wireless Sensor Network	N/A	N/A	Broadcast	Only routing	♡
10	Cluster [166]	-	Sink	++	Broadcast	Only routing	Development of Fuzzy
11	RS-CPR [167]	Relay Selection Consecutive Packet Routing	Source	++	Broadcast	Only routing	◇
12	G-WHARP [168]	Green Wake-up and HARvesting based energy-Predictive	Sink	++	Broadcast	Only routing	*GWNs

Single-hop : + , Multi-hop : ++ , *Green Wireless Network

† : Reducing energy consumption of WSNs

♡ : Operation mechanism of dual routing protocol

◇ : Improving WuR-EnabledWSNs performance

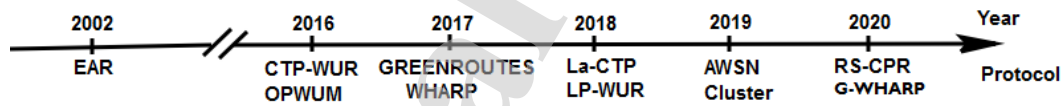


Figure. 12: Illustration of the initial standardization timeline of WuR Based on routing protocol designs.

in a multi-hop system as a sort of solution. However, the issue of utilizing a WuR as a recent component with a wireless connection to an existing node is considered incompatible among the ranges. As it is known, WuR technology owns shorter ranges despite the capability of the stronger power radio to achieve it. Specifically, packets require to be routed via larger tracks than those related to the main radio. This latter determines the data latency and the network lifespan as well. Figure 12 shows a timeline of routing protocols designs in progress. On the other hand, Table 7 presents the WuR-based routing protocols, mentioned in the timeline figure, followed by their reference numbers, abbreviations and other characteristics and targeted applications that we are going to develop later on, while Figure 13 illustrates the routing protocols followed by their corresponding characteristics.

The major purpose of energy aware routing (EAR) protocol [157], proposed in 2002, is to enlarge the network lifespan by selecting optimal paths. These latter were selected, relating to the power storage, so that any path can consume its energy briskly. A cross-layer EAR protocol employed sub-optimal paths in order increase the network lifetime. For the EAR's MAC layer, it is in charge of all the remaining nearby positions and their attended essential energy.

Afterwards, this list of all the adjacent and metrics are examined by the network layer in order to take resolutions related to packet routing. In the end, to transmit data, the MAC layer sends a WuS on the broadcast channel and it does not treat end-to-end latency.

Besides, based on Figure 13, EAR, OPWUN, GREEN-ROUTES, WHARP, RS-CRP and G-WHARP protocols have

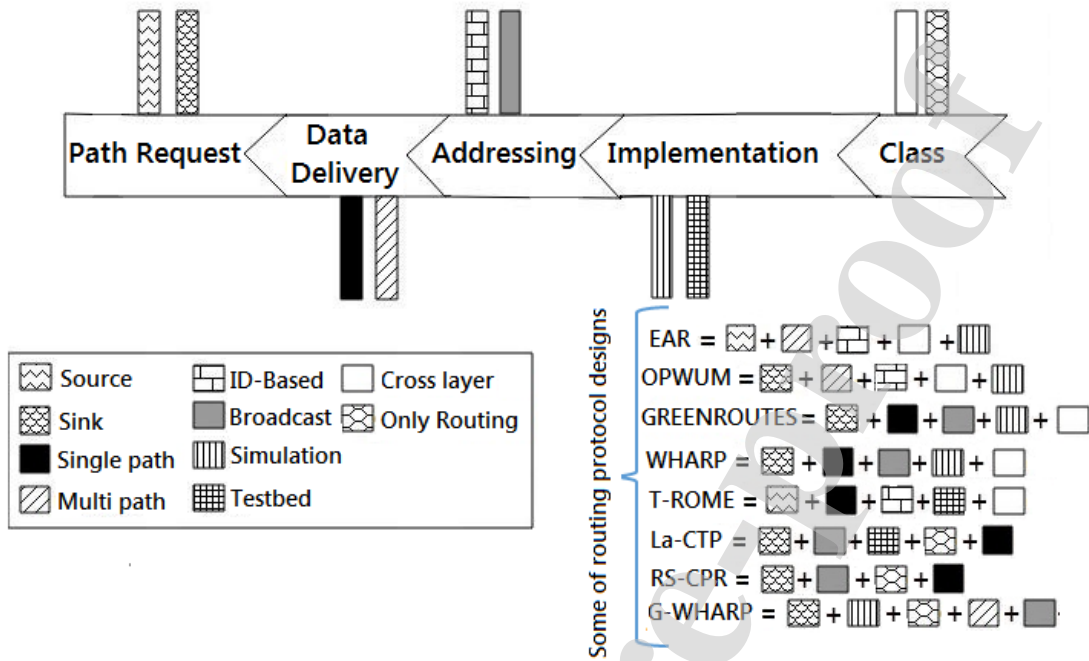


Figure. 13: Some of WuR based routing protocol technologies.

only been estimated through simulations. However T-ROME and La-CTP protocols have been tested by testbeds.

In 2016, OPWUM [159] requires a cross-layer MAC protocol supporting WuRx in order to choose the greatest receiver between all its neighbouring nodes through energy usage. To avoid clashes among wake-up beacons, a total channel assessment (CCA) is improved, employing the WuTx. Afterwards, an RTS-CTS is switched among the WuTx and WuRx before transmitting any data packets through the main radio. In addition, OPWUM has an important characteristic which all the next hop relay chosen phase is performed by wake-up beacons.

Another cross layer routing protocol T-ROME is attended in [162] in 2017. Regarding the MAC layer, T-ROME employs RTS/CTS messages in order to decrease packet collisions. The next hop node is selected effectively utilizing link quality assessment in order to control on condition that the relay node is included in the wake-up range. If so, the data is transmitted immediately to the specific node without moving from each child to its parent [162]. Moreover, T-ROME stocks energy by ignoring nodes throughout data communication. Applying to a testbed, the article has proposed that T-ROME performs better than CTP-WUR regarding number of hops needed to achieve the sink while reducing power consumption and latency.

As follows, S. Basagni et al. [160] proposed GREENROUTES, a routing protocol for green networks and for energy harvesting-based WSN. This latter enhance auto-powered technologies in order to reduce the energy storage re-

quirement. So it has been always compared in performance with Energy Harvest Wastage-Aware (EHWA), which GREENROUTES has the capability to transport to 40% extra packets with lesser energy consumption and faster packets distribution, to the sink.

As known, CTPWUR, GREENROUTES and WHARP are assembled together for green wireless networks where nodes are able of EH and reach performances through a variety of performance metrics. The results of their simulations revealed that GREENROUTES and WHARP sustain high latency and energy consumption. However, CTP-WUR gets higher and lighter performance due to many proactive paths of identifying routes [169].

In 2018, G. Sun et al. [163] proposed La-CTP which is employed for feasible EH-WSN applications. Based on a 100-node testbed, the experiential results revealed its efficacy in which La-CTP can be managed with loops through eligible throughput and low cost.

Afterwards, a novel dual routing protocol system for aerial sensor networks was suggested by L. Tan et al. [165] in 2019. This operation specifies a routing protocol that matches two network stages, known as dynamic stage and steady stage. Furthermore, the simulation system develops a dual routing protocol that can provide very efficient performance, upgrade the energy efficiency used, and lengthen the existence of the network.

Ultimately, in 2020, G. Koutsandria et al. [168] concentrates on green wireless networks, in which nodes are performed, including WuR technology potentiality and EH.

Thus, this latter shows G-WHARP and its performance is discussed through GreenCastalia simulations. It designs WuR technologies, EH and the computational power required in order to determine the Markov decision process (MDP). It also absorbs more than 34% and lesser than 59% energy comparing to GREENROUTES and CTP-WUR.

In the next section, we are presenting the classification of WuR based on mobility/static states, range, energy consumption and other several characteristics.

5. Classification based on mobility, data rate, range, technology, energy consumption

This section proposes a classification based on numerous elements such as frequencies, mobility, data rate, sensitivity range, energy consumption, power supply, technology, modulation/demodulation and on circuit type, shown in Table 8.

However, some circuits or technologies are not suitable for mobility. Most of the WuR circuits are rather used in static mode, i.e. the card does not move. Mobility is another ranking criterion. Another criterion is the energy recovery method of the WuR cards: the recuperation of ambient energy (extracted from several radio electric sources), recovered by an emitter beam which points at the WuR card, recuperation with a hybrid circuit which recovers the ambient radio electric energy and which is combined by a recuperation from another solar source, wind, movement, etc.

Many areas of research are working through node mobility in wake-up schedule design shown in articles [170] and [171]. Countless strategies insist on the sink and sensor nodes which are immobile and stable. Due to the shortage of assortment demand which makes them vigorous to network topology conversion, Asynchronous and synchronous schemes are better contestants for these structures. In the node mobility case, schemes need coordination that is probably not connected to an optimal schedule. So the behavior of WuRs is still undetermined in such circumstance. In the following, we have mentioned and illustrated the most essential of the selected articles located in Table 8 by accentuating on the significance of these characteristics and their effects as things progress in the world of IoT technology.

In reference [36], S. J. Marinkovic et al shown an unusual WuR design appropriate for WBAN utilization. It calculated the effectiveness of its receiver, applied in the ISM 433MHz band. It shows, as results, its radio according to shortest power solution which contains receiver abilities, revealing listening consumed power, higher than 10 and lesser than 100 times, lower than other WuRx. In addition to -51 dBm of the sensitivity range in order to convert the values of receiver's circuit, it manages with various data rates and frequencies (in this work 433 MHz and 2 to 80 kbps corresponding) and leads the WuR to a nice decision for WBAN utilization, where low consumed power (270 nW) is an important feature. It can be also adjusted to short range WSN topology.

P. Le-Huy et al. proposed in [43] a total WuR and its simulation were included. To get a PWM signal, a zero-bias

Schottky diode envelope detector was employed. Through this signal, the address decoder produces clock signal essentially to activate its decoding circuit. The overall mean of consumed power is lesser than 20 μ W, with a 1 V of power supply. In this article, they discussed about employing directional communications in order to enlarge the efficiency of WuR's sensitivity (-53 dBm). Furthermore, they selected 0.13 μ m CMOS technology due to its accessibility and low cost. In addition, short energy is demanded in order to transmit the WuCs and additional power is added to ease the decoding performance.

Nevertheless, in article [50], M. Spinola et al. proposed the total primary application of a WuR with consumed power around 10 μ W. For the design and architecture, it is effectively affected by WSN applications in which the low range wake-up ability is well performed. Consequently, the total power consumption of communication and its latency is decreased concurrently. In addition, the demodulation of the receiver is by ON-Off Keying at 100 kbps. A 120 nm CMOS chip involves the analog front-end and absorbs mainly 7.5 μ W for 1.5 V power supply and the digital signal processing is executed onto an FPGA.

In [97], Y. Wang et al. gave a modern low power edge identification circuit. For the occurrence of signal falling edge, the suggested architecture started by a little voltage difference among the gate and source terminals of a MOS transistor. Customized designs, that can support LO frequency accuracy, had been employed in Wake-up receiver circuits and had the range of sensitivities from -82 dBm to -72 dBm. Nevertheless, their high power consumption is more than 50 μ W which is unsuited for applications that need low consumed energy according to limited interval.

Next in article [99], J. Lim et al. exposed the highest sensitive RF wake up circuit employing a passive voltage multiplier was created and executed into 0.18 μ m CMOS technology. They thus realized a high sensitivity through native NMOS transistors in the passive voltage multiplier and achieved a sensitivity of -28 dBm in order to get an output logical signal. The WSN system and WPAN system can involve the suggested wake-up circuit that increases dramatically the battery life.

The paper [103], S. Oh proposed a 116 nW of power consumption WuR including crystal reference and baseband development. The front end works on a broad frequency range and must be illustrated between MICS band (402-405 MHz) and ISM band (915 MHz and 2.4 GHz) with -45.5 dBm, -43.4 dBm, and -43.2 dBm sensitivity range. Furthermore, the wake-up radio own an OOK chip rate of 12.5 kbps and employs a 0.5 V power supply for sub-threshold baseband processing and a 1.2 V power supply for RF demodulation and the crystal reference.

Lastly, Y. Shuangming et al. work [104] suggested a non volatile low power baseband processor with WUI receiver for LR-WPAN transceiver. It contains main receiver, WUI receiver, power management and NVM non-volatile memory. The baseband processor is created and proved via an FPGA board. Besides, the power consumption of processor

Table 8 Comparison of reported wake-up devices.

Ref.	Frequency	Mobility	Data rate (Kbps)	Sensitivity range (dBm)	Range (m)	Energy consumption	Power supply (V)	Techn.	De/Modulation	Circuit type
[36]	433 MHz	yes	2 to 80	-51	<2	270 nW	1.5	HC MOS	-/OOK, PWM	Semi-Passive
[43]	2.4 GHz	yes	50	-53	4 to 5	<20 μ W	1	0.13 μ m CMOS	PWM/PWM	Active/Passive
[44]	868 MHz	N/A	100	-52	~3	2.7 μ W	0.9	no application MOS circuit simulation	Passive/OOK	Passive
[25]	915 MHz	yes	100	-41	N/A	98 nW	1.2	0.13 μ m CMOS	-/OOK	Active/Passive
[50]	2.4 GHz	yes	100	-53 -57	N/A	7.5 μ W 6.5 μ W	1.5	120 nm CMOS chip	OOK/OOK	Passive
[97]	915 MHz	no	10	-82 to -72	N/A	>50 μ W	1	N/A	N/A	Active/Passive
[98]	408 MHz	no	50	-55	N/A	100 μ W	1	180 nm CMOS technology	-/OOK	Active/Passive
[99]	2.4 GHz	no	N/A	-28	N/A	N/A	1.5	0.18 μ m CMOS	OOK/-	Passive
[100]	2.4GHz	N/A	10 50	-97 -92	N/A	99 μ W	0.5	65nm CMOS	-/OOK	Passive
[102]	2.4 GHz	N/A	100 10	-64 -69	N/A	51 μ W	0.5	90nm CMOS chip with MIM capacitors	-/OOK	Active
[103]	402-405 MHz MICS Band 915 MHz ISM Band 2.4 GHz ISM band	no	12.5	-45.5 -43.4 -43.2	6m (for 400 MHz and -40dBm)	116 nW	1.2 0.5	130 nm CMOS	RF/OOK	Active/Passive
[104]	800MHz/2.4GHz	N/A	250	N/A	N/A	TX: 5.1 μ W RX: 28.2 μ W	1.8	0.18 μ m CMOS	-/OQPSK	Passive/ Semi-Passive
[129]	2.4 GHz	no	4	-45	< 25	RX: 360 nW to 78 μ W	3.3	Discreet circuit	OOK/OOK	Semi-Passive

has two values, either for transmitting (5.1 μW) or for receiving (28.2 μW). The WUI receiver comes thus to notably decrease the mean power consumption of transceiver. And the NVM comes to keep away from the waste of the state information effected by power frustration and energy loss.

In the following section, we will see different areas where WSNs and their technologies can be applied. In the end, we will conclude the article by giving a general conclusion that summarizes all the sections explained before.

6. Key Application Areas

This section will illustrate some of the main application areas in which the technologies mentioned previously have a principal role to process. More precisely smart technologies based on WSN wireless sensor networks are efficiently utilized into several applications in order to observe and control various conditions based on environmental, personal health and other characteristics. Therefore, we examine the key application areas where the passive/active WuRs can be employed.

In Table 9, as we noticed, the majority of circuits have few real applications regarding passive or semi-passive circuit technology which is not yet mature for a large-scale deployment or in a real environment. Indeed, the first applications most often use active circuits. Each type of circuit is designed for a particular application and cannot be generalized or extended to other applications. So we have tried to classify them in Table 9. Furthermore, the simple technology readiness levels (TRL) are proposed to classify WuR circuits for applications areas. Four categories are chosen instead of the nine specific TRL levels. Our simplified TRL are organised from bottom to top as: Idea* (TRL=0-3), Prototype^o (TRL=4,5), Validation* (TRL=6,7), Production^o (TRL=8,9).

6.1. Healthcare Applications

In the medical field [18], the current research is based on wireless body area networks (WBAN) since this technology is recently considered the most sensor network technology employed of all time.

In particular, this field shows a research of the propagation inside and outside of the human body passing by MAC-protocols, routing protocols and security. Figure 14, which is inspired by article [18], shows WBAN passive WuR for medical applications. Some of these networks sensors listed in the mentioned figure are connected whether on clothes or the body of the patient or even inserted under the skin. In order to obtain appreciable health care, medical applications depend on the variety of sensors and the wireless nature of the network. This latter help the patients especially who have chronic diseases to live a normal life. For instance, implantation of WBAN sensors that calculate heart rate or blood pressure or other serious cases. In this case, the patient has greater physical mobility and is no longer obliged to stay in hospital [18]. Considering the sink node is mainly in the same area with other sensor nodes, the range parameter is not

Table 9
WuR based on realistic and feasible applications.

Application areas	References	Power source	TRL
*UAV	[11, 172]	Active	o, *
*UAS	[1, 12–14]	Passive	o, *
Green IoT	[33]	Active	*, o, o
		Passive	*, o, o
Indoor Localization	[173–175]	Active	o, *
Smart Grid	[8, 176–178]	Passive	*
Smart Gate	[179, 180]	Active	o, *
Smart Building	[181–184]	Active	*
	[17–19]	Active	*
Healthcare	[185]	Passive	*, o
†IIoT	[15, 16]	Active	*
Smart Wildlife Monitoring	[21, 171]	Passive	o, *
**WBAN	[186–188]	Active	o, *
WSN for urban area	[189, 190]	Active	*, o
Smart City	[2, 20]	Active	*, o, *
		Passive	*, o, *
Security systems	[30, 191]	Active	*, o

* Unmanned Aerial Vehicles, * Unmanned Aerial System
**Wireless Body Area Network, †Industrial Internet of Things
*Idea, ^oPrototype, *Validation, ^oProduction

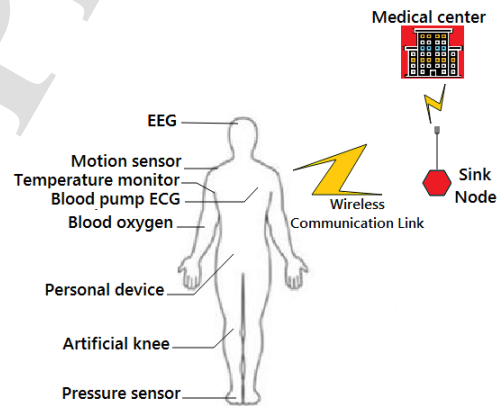


Figure 14: Description of intra/extra body communication based on WBAN passive WuR [8, 185].

necessarily required to be in long distance. consequently, the medical application accepts passive WuR.

6.2. Environmental Applications

Environmental monitoring applications are mainly based on WSN which are worthy to perform the ability of a passive WuR method. It is a collaboration of many sensor nodes distributed all over a city (smart city [2, 20]) or it could be integrated into many other applications such as smart gate [179], smart building [181–184], security systems [30, 191], indoor localization [173–175], WSN for urban area [189], smart

wildlife monitoring [21, 171], green IoT [33], industrial internet of things (IIoT) [15], unmanned aerial vehicles/system (UAV/UAS) [11] [172] and many others.

- **Smart City:** Nowadays, Smart cities have become one of the most current and complex scientific topics for several reasons and serve citizens in various domains. For city employers and citizens, this topic allows giving more preferable efficient services. Technically, smart cities show a large environment of using equipment and machines in order to capture data, have a storage capacity and for processing [20]. And for internet scientist, This latter moreover becomes the top enormous installments of the IoT concept. Smart city applications are generally installed in diverse sections: the aggregation networks which link sensors/actuators with the general network, the data acquisition and actuation and others [20]. But the most expensive equipment of a smart city is the aggregation network and the sensor/actuator.

This schematic in Figure 15 is a common representation of a Smart city that employs sensors to observe the city, a network to save data, processing abilities to extract results from the data and a group of actuators to be manipulated by the processing elements. Besides, the aggregation network is needed in order to communicate the sensor node with the platform in which data is processed and stored [20].

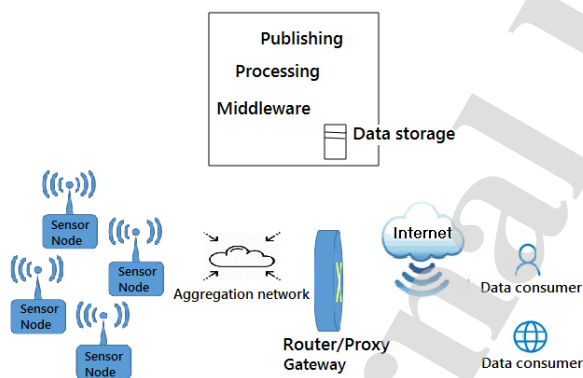


Figure 15: Schematic of a classical smart city platform.

- **Smart Wildlife Monitoring:** This smart application is one of the potential environmental application of the passive WuR that is indispensable for this application and tracking of various species, habitat employment, population demographics, snaring and poaching incidents [171]. Using detector networks has earned momentum in the past few years. Thus, we will not be concerned in case of periodic operation, if there is any interactivity between animals throughout an inactive time of the sensor node, it will not be recognized in time. The employment of WuR method for lifetime supplement in wildlife monitoring applications is considered suitable,

so the purpose of wake-up radio for wildlife monitoring can be doubled: either it can be operated as a contact sensor or as an initiator for a better data transmission [21].

For the sink nodes, they are set at strategic locations where the animals are gathered or moved around. if they are located in the range of the sink nodes, the WuR will trigger the radio on them. The collars can thus send the collected sensor data through the main data transceiver to the data collector [31].

Eventually, the monitoring system proceeded in a remarkable reduction in the energy wastage in the sensor nodes. Therefore, we can conserve more energy as a consequence. So the collars may live for many years and the battery substitution and recuperation value can be conserved.

- **Smart Gate:** This application is described as WSNs interior buildings (Fig.16) which are utilized to extract sensor data and to run actuators. The nodes are required to work for a long period with a single battery. When utilizing a standard Wi-Fi connection, the node's battery might be drained after a limited time (few hours) because of idle currents in receive state. Thus, sensor nodes along with WuRx can extend the lifetime of the sensor network for many years [179]. However, no gateway can link itself to the Internet and can after transmit the unique coded WuS required by the WuRx on the nodes. In this example, the

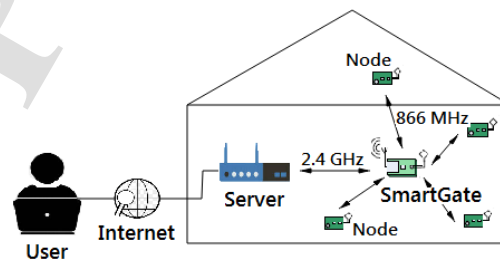


Figure 16: SmartGate system summary [179].

purposed solution is to fill this gap by presenting a Smart Gate which is a gateway with two transceivers that are integrated on a single printed circuit board (PCB).

For the Wi-Fi module, it links all alone to a Wi-Fi network and starts listening for arriving messages. A CC430 MCU reads the arriving Wi-Fi messages and makes the suitable WuS with 16-bit address coding. For the next step, the WuS is transmitted out through the integrated CC1101 transceiver core. A woken-up node is going to read it out and will send it back to the gateway, where it is going to be filled up into a TCP/IP packet and transmitted back to the user. The role of the gateway permits the execution and realization of a WSN with WuRx [179].

- **Security System:** Conventional security and surveillance structures, based on excessive power central cameras, generate alarms if unapproved objects are detected. Such sys-

tems demand installation nearby the stationary power source due to a large image processing algorithms. WuRs that have power camera systems low price are utilized in order to observe unapproved objects or anonymous people. So the monitoring zones can be protected with many WuR based on autonomous and stationary camera systems which are connected in a wireless manner to the main system.

When an intrusion is captured then recognized through wake-up cameras, the camera system can be activated for security operation. Moreover, to decrease the camera tasks, low power detectors with WuRs can be attached as an independent network tier [30].

Duty cycling the WuRs on camera nodes was firstly used to decrease power consumption but it produces in the same time response latency. However, there is an alternative protocol solution which is MAC protocols based on always ON WuRs. Regarding to routing protocol, an effective value and an authentic multi-hop communication network is demanded in order to take place by efficient monitoring of the area.

- **Indoor Localization:** In the last few years, indoor localization has been one of the major defiance in the engineering domain, since it is known by using localization systems based on Global Positioning System (GPS) that are not accessible there [173]. A basic indoor localization system applying an ultrasonic rangefinder in order to decrease the difficulty of the system as well as able to chase both low- and high-speed human movements.

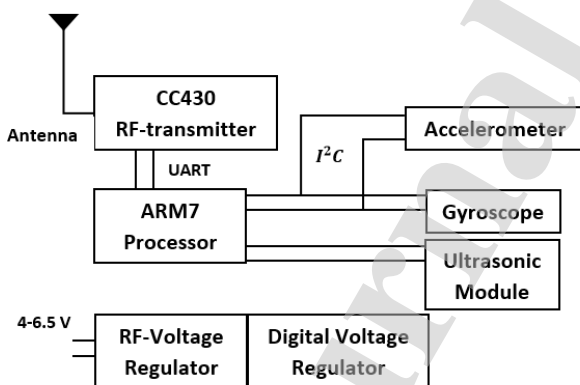


Figure 17: Indoor localization hardware design [174].

An indoor localization system prototype contains four main parts: inertial sensors, ultrasonic rangefinder, microcontroller and wireless communication (Fig. 17). The sensor and distance signals are acquired from inertial sensors and rangefinder [174]. Then, the required conclusions are evaluated from the received signals through microcontroller. The 3-axis accelerometer and gyroscope are employed to give inertial sensor data. The SRF10 ul-

trasonic rangefinder is used to calculate the distance between the foot and ground for still-phase detection [174]. Each one has a digital output. Microcontroller CC430 is employed for algorithm installation and RF communication and all the sensed data communicate at 36 Hz.

- **WSN for urban area:** This part provides a survey of WSN utilization in urban areas in which it categorizes each application scenario accurately (Fig.18). There is an innovative contemporary integration of sensor networks into some application cases. The fine line between wireless sensor networks, ad hoc networks, mesh networks and other familiar networks has been enhanced. So, it is almost unfeasible to compare between them [189]. Every sensor node is qualified differently depending on their environment. For example, if the sensor node is employed underground it will definitely have transceivers with high transmission power to get rid of noisy channel attenuation. If it is located under water, their external casing will be designed in order to resist the effects of moisture and be characterized by waterproof.

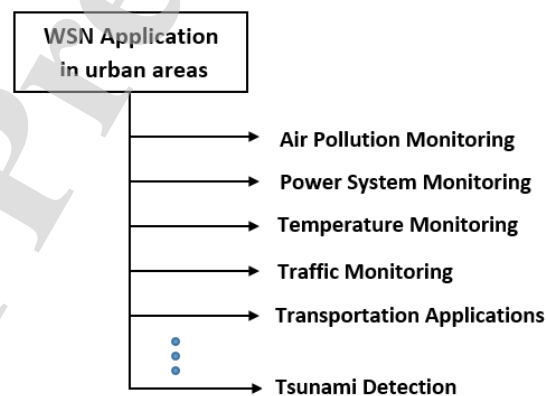


Figure 18: Some of WSN applications in urban areas.

- **Green IoT:** Low power devices have demonstrated their significant jobs in numerous green Internet of Things. Nevertheless, to extend the operation time of the devices, especially improving the battery capacity, it turns out to be a complex challenge in view of the essential restraint of limited form. Therefore, they count on new a physical layer and medium access control schemes. So since 2017, this need permitted IEEE 802.11 Task Group "ba" (TGba) to initiate the normative work related to wake-up radios. This new technical characteristic suggests considerable perceptions of IEEE 802.11ba. It includes deployment scenarios, physical operations (such as waveform, modulation and synchronization design), MAC performances (such as WuR duty cycle, WuR mode, channel access scheme) and the format of a MAC packet data unit. These previous observations help in accelerating the research of IEEE 802.11ba WuR and empower the next generation green

IoT [33].

- UAV/UAS (Unmanned Aerial Vehicles/System):** In the past couple of years, this technology has been employed to fight forest fires and aid in search and rescue operations at practically zero risks. In general, remote sensing belongs to any non contact method through which the object space can be detected. Basically, remote sensing was employed for satellite and airborne platforms through optical and radar sensors. Remote sensing is thus a highly developed technology, largely driven by imaging sensor developments and highly growing performance of the information infrastructure. Furthermore, latest platforms are presented specifically for unmanned aircraft system (UAS) and unmanned aerial vehicle (UAV) [172]. UAV or otherwise called drones are included in autonomous navigation, positioning, and in typical robotics technologies. What distinguishes UAVs is its small shape, low price and malleable in imaging payloads as remote sensing platforms comparing to standard airborne platforms such as satellites or aircraft [11]. Nowadays, UAVs have integrated the newest GPS technology. The multi-motor and small UAVs can fly according to the predecided GPS waypoints. Several developed drones have been prepared with less expensive vision sensors. Moreover, it receives a lower level of flying beyond line-of-sight due to their sensibility capability. [11].

- Industrial Internet of Things (IIoT):** One of the application sectors of IoT is the industry. The Industrial IoT is made of networks, detectors and services to manage production operations [15] and for real-time monitoring of processes through dynamic modelling or automatic learning guided by sensor data [192]. Besides, several IIoT devices are resource restricted, which obstructs the employment of traditional security aids for them. However, numerous authentication protocols have high computing needs in order to resource-constrained devices. In [15], there is an authentication protocol for restricted resource IIoT devices which is based on the lightweight functioning xor, a hash function, addition and subtraction. In Figure 19, the architecture contains a sensing domain, web services, cloud server, and user applications. The sense domain consists of three parts: control node, gateway, and sensor nodes. The sensor nodes are made from resource-constrained devices that are in charge of gathering and sending contextual data to the second part: the gateway. This latter stocks the collected data in buffers and transfers them to the control nodes, which collect the information from diverse gateways and give new direction networks with web services. The networks in Figure 19 work as a link between the sense domain as physical objects and their cloud as a virtual representation. The point of view of this scheme is energy efficiency in order to accomplish a green IIoT [16]. Because of a large number of sensing nodes presented in sensing domain, the Industrial IoT system absorbs a significant amount of energy. The suggested protocol goes

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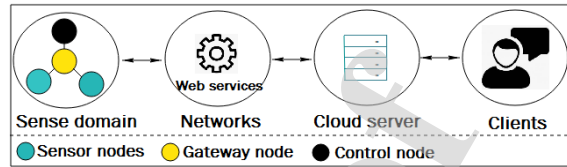


Figure. 19: Energy-efficient design for IIoT.

along with the perspective of low computing-resource employment on the sensor devices, which reduces the energy cost of the IIoT system and extending the battery life of the sensor devices.

6.3. Smart Grid

Another new sensor technology is the smart grid that includes communication, observation, control, and testing potentialities to the electricity grid in order to enhance the electricity reservoir chain. Therefore, it authorizes high system throughput and low energy consumption as well by authorizing capabilities to transmit the electricity from one area to another [8].

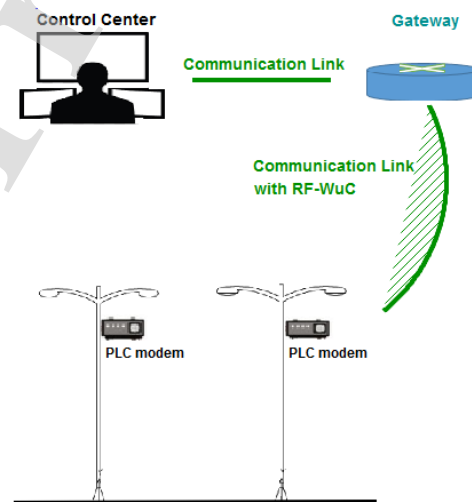


Figure. 20: A representative schematic of smart grid application tested in street light poles PLC.

The main challenges that confront smart grids are maintaining productivity in communication. One of the preferred technique by which smart grids transmit spot to spot communication is PLC. So the energy efficiency gradually decreases in periodic communication as for example the smart street lighting as shown in Figure 20.

The PLC modem is related to the passive WuR. This permits the modem and the attached load, which is the street lights, to persist into a deep sleep and only wakes up after collecting a signal. Some of passive wake up proposed pro-

protocols in [193] and [194] banish energy inadequacy by eliminating idle listening while the machines are on stand-by.

For suitable protocols in smart grids, protocols for wireless communication require high and quick recognition at the shortest energy cost. According to MAC protocol, this latter must bring together on the latency improvement and on the multi-hop characteristic of the network. However, latency could not be processed here, because it depends on the network protocol. Latency, by definition, is the delay to transmit an information between two devices. Nevertheless, many applications don't treat this aspect.

7. Conclusion

This paper reviews current knowledge on the concepts of low energy WuR technology: active, passive and semi-passive WuR. We started by giving the dimensions of WuRs, then physical architectures of WuRs circuits and the properties of each of their distributed technologies in different application domains. A state of the art of each WuR power source has been discussed.

For any circuit either active or passive, the MAC protocol depends on the number of users or services for specific applications. Thus, it has been improved in WSNs in order to lessen consumed energy by allowing nodes to work on sleep and wake-up cyclically. In this paper, we have shown a timeline of the MAC, followed by a table for the diverse protocols references with a scheme which describes some of MAC protocols followed by their characteristics.

Furthermore, many solutions and research opportunities have been shown up in order to solve the difficulties of WSN that appear in the range of the base station. Thus, the routing protocol is presented to solve these challenges. The data is routed in a multi-hop system as a sort of solution. The same methodology of work that was adopted in MAC protocol was adopted in routing protocol from timeline, to different protocols references until presenting the characteristics of each routing protocol.

Moreover, some circuits or technologies are not suitable for mobility, so most of the WuR circuits are rather used in static mode. Hence, we highlight this concept by drawing a table representing a classification based on mobility, data rate, sensitivity range, energy consumption and other features.

Among all the application areas where these combined structures can operate are developed, the field examples chosen are healthcare applications, environmental applications such as smartCity, smart wildlife monitoring, smartGate, security systems, indoor localization, WSN for urban area, green IoT and UAV/UAS (unmanned vehicles/system), and ultimately the smartGrid application. Future developments based on this topic are always in progress to serve the community in various fields, so it can yield extremely higher performance levels.

To conclude, this recent overview summarized the WuR circuits such as active, passive and semi-passive through the physical, MAC and routing layers, where all are classified

into diverse criteria. However, we have noticed that the WuR passive circuit is not easy to design and to implement in real solution, because it depends of the envisaged application. Thus, the TRL of passive WuR circuit are an open challenge until it integrates in commercial IoT devices.

Acknowledgment

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Acronyms

ADC Analog-to-Digital Converter

ASK Amplitude Shift Keying

BiCMOS Bipolar Complementary Metal Oxide Semiconductor

CMOS Complementary Metal Oxide Semiconductor

CTS Clear-To-Send

dBm decibel-milliwatts

EH Energy Harvesting

FSK Frequency Shift Keying

FSO Free Space Optics

IF Intermediate Frequency

IIoT Industrial Internet of Things

IoT Internet of Things

ISM Industrial, Scientific and Medical

LO Local Oscillator

LOA Laser On Air

MAC Medium Access Control

MCU Micro Controller Unit

MICS Medical Implant Communication System

MOSFETs Metal Oxide Semiconductor Field Effect Transistor

NVM Non-Volatile Memory

OOK On Off Keying

PCB Printed Circuit Board

PIE Pulse Interval Encoding

PLC Power Line Communication

PWM Pulse Width Modulation

RF Radio Frequency

RFID Radio Frequency Identification

RTS Request-To-Send

SMD Surface Mounted Device

SN Sensor Network

TRL Technology Readiness Levels

WBAN Wireless Body Area Networks

WSN Wireless Sensor Network

WuCs Wake-up Calls

WUI Wake Up Identification

WuR Wake-up Radio

WuRx Wake-up Receiver

WuS Wake-up Signal

WuTx Wake-up Transmitter

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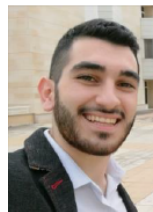
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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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