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Review

A Systematic Review on Wake-up Radios Applied to Wireless Sensor Networks

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Abstract: Wireless Sensor Networks (WSNs) are the backbone of many monitoring applications, especially in the Internet of Things (IoT) context. However, efficient power management becomes a critical challenge when sensor nodes rely on disposable batteries. The deployment of WSNs must ensure coverage and connectivity, but the resulting distribution of nodes and underlying protocols directly impact the network's lifetime. The concept of ideal power consumption, where nodes are active only when strictly required, is fascinating. One innovative way to coordinate node activation is through Wake-up Radios (WuRs), devices that keep listening for an external activation signal while the remaining node's components stay off. To further extend power savings, a passive WuR variant allows the complete system to remain off: The device captures the activation signal's energy to initialize the radio, waking the rest of the system up. The active variant provides a way to extend the activation distance range compared to the passive one and its associated energy savings sit between the passive and traditional methods (non-WuR) to toggle a node between active and sleeping modes. This study presents a systematic literature review regarding WuRs applied to WSNs. Our review presents results concerning the works' primary research outcomes and limitations, the WuRs' roles, and prospective future works.

Keywords: Wireless Sensor Network, Wake-up Radio, Systematic Review

Introduction

Wireless Networks (WNs) exist in many formats and configurations. Without wires, communication is possible whenever and wherever the communicating parties can link through a radio channel. However, such channels are much more prone to interference and security concerns and provide less capacity than wired communication.

WNs can rely on *(a)* a communication infrastructure or *(b)* a self-organizing structure. Wi-Fi and Mobile/Cellular communication are examples of the former. In the latter scenario, the primary representatives are the Mobile ad hoc Networks (MANETs) (Perkins and Royer, 1999; Johnson *et al*., 2007; Broch *et al*., 1998; Kanellopoulos and Cuomo, 2021; Rubinstein *et al*., 2006). Meanwhile, as a hybrid approach, we have the Wireless Sensor Networks (WSNs) (El Khediri, 2022; Rawat *et al*., 2014; Kandris *et al*., 2020). In many applications, WSNs enable the Internet of Things (IoT) (Lazarescu, 2017).

Analytical studies (Gupta and Kumar, 2000) show that ad hoc networks' capacity does not scale when the communicating nodes are stationary; instead, the capacity decreases as the number of nodes increases, eventually dropping to zero. This situation remains true even when splitting the channel into multiple sub-channels. On the other hand, when node mobility is present, it creates a more diverse environment, increasing the network capacity (Grossglauser and Tse, 2002a-b).

MANETs connect mobile users and devices following a self-organizing and multi-hop approach, with many solutions addressing the vital problems associated with the communication layers (Rubinstein *et al*., 2006). WSNs usually support applications aiming to capture some environmental phenomena. In most such scenarios, nodes are stationary, with sensors and actuators located at Points of Interest (PoI), where nodes must gather the critical data for the main application. WSN variants also support hierarchical architectures, including mobile nodes (e.g., Unmanned Aerial Vehicles, UAVs) acting as messengers or collectors (data mules).

The WSN must meet the application's specific cost, scalability, reliability, maintainability, and security requirements. Therefore, its foremost objective is to ensure coverage and connectivity to the appropriate agents (internal or external to the monitoring environment), considering all the constraints and the expected Quality of Service (QoS).

Depending on the environment's characteristics, after deploying a WSN, one hopes it will work without direct intervention for an extended period (i.e., up to several years). All the system's critical components must function correctly during the whole network lifetime (i.e., nodes with failing components might compromise the entire application). Batteries, supplying energy to the nodes, are usually the system's weakest link: rechargeable batteries rely on some energy harvesting mechanism (e.g., solar panels) (Qureshi *et al*., 2022); in contrast, disposable batteries (i.e., non-rechargeable) typically provide larger energy capacity than rechargeable batteries (assuming the same physical volume) while needing their replacement once they become depleted. Such tradeoff must be part of the system's design, with the target application as its primary driver.

Efficient power management is not just a consideration but a paramount necessity in WSNs, especially when no energy harvesting is available. Most solutions share the distinct scheduling of active periods (higher power consumption) and inactive or sleeping periods (lower power consumption). The proper arrangement of such states extends the battery's lifespan and, therefore, the lifetime of the entire system. The power management mechanism ensures the application handles all critical events within time constraints.

A node can manage its transition to an active state following a predefined guideline or schedule, specifying when it is sleeping or in a duty cycle. Coordination between transmitters and receivers is required so that both are active simultaneously. Likewise, one seeks to minimize the periods in which a node is unnecessarily active.

Otherwise, a node can stay in a deep sleeping state with minimal power consumption, waiting to be awakened by an external signal channeled to a Wake-up Radio (WuR) (Da Silva *et al*., 2019). Such a radio is usually the single active component of a sleeping node. Once a valid wake-up signal is received, a procedure starts the remaining node components up.

It is an in-band system with the only radio available for regular data communication as part of the WuR receiver/transmitter. Otherwise, an out-of-band strategy consists of having a separate device for the WuR: Two radios might increase a node's cost but usually lead to reduced power consumption. An out-of-band WuR may have a limited range compared to a regular radio due to the differences in transmission power levels. However, depending on the duty cycle pattern and the available radio's sleeping state modes, opting for an in-band WuR might pay off (Djiroun and Djenouri, 2017).

While traditional WSN nodes can also achieve energy efficiency by operating under shallow duty cycles, we highlight two main advantages of the WuR approach: (a) WSN nodes using WuRs do not need to follow regular activation scheduling, and (b) the energy consumed by the WuR node while sleeping can be at least one order of magnitude smaller compared to the sleeping energy of regular Commercial Off-The-Shelf (COTS) WSN nodes.

Typically, out-of-band WuR nodes have an improved energy efficiency than in-band WuR systems if the main radio used for data communication has a significant power consumption in listening mode (e.g., from a few to dozens mWs). On the other hand, some WuR receivers operate with an average sleeping power below one mW (Da Silva *et al*., 2019; Sánchez *et al*., 2012; Hambeck *et al*., 2011). While these out-of-band WuR modules may not be able to perform the regular tasks of the main radio, they are still an efficient way to wake a WSN node.

Some WuR receivers can also undergo a deep sleep state by achieving power levels close to zero, increasing power savings even further (Piyare *et al*., 2017). In this case, the radio is passive, requiring the incoming signal's energy to start it up. The main drawback of such an approach is that the system must capture a minimum amount of power from the received signal, which might take a considerable time. In general, passive WuRs are only practical for very short distances (i.e., less than a few meters) between the transmitter and the receiver; otherwise, it might take several minutes to wake a node up (Da Silva *et al*., 2019). In addition, a passive WuR also implies an out-of-band WuR solution if the design of the passive WuR device only addresses the capability of activating the remaining components of the node rather than performing wireless data communication.

This study systematically reviews the literature on WuR applied in WSNs. It focuses only on works that rely on WuRs as essential in addressing research problems in WSNs. To our knowledge, this is the first work to address our research topic. Table (1) shows the essential acronyms and abbreviations and their complete forms used throughout the paper. The remainder of this study is structured as follows. The next section presents the basics of WSNs, while the following one delivers the basics of WuRs, including a taxonomy for WuR devices. Then, we outline our research methodology, after which we present the literature review and our research results. The last section presents our findings.

Table 1: Acronyms and abbreviations

ATS	About To Send
CCA	Clear Channel Assessment
CH	Cluster Head
COTS	Commercial Off-The-Shelf
CoWu	Content-based Wake-up
CTS	Clear To Send
DoS	Denial-of-Service
DS	Dominating Set
EDIT	Early Data Transmission
ES	Early Sleep
IoT	Internet of Things
LoRa	Long Range (radio)
LoRaWAN	LoRa Wide Area Network
LOS	Line-Of-Sight
MAC	Medium Access Control
MANET(s)	Mobile ad hoc Network(s)
MCU	Microcontroller Unit
ML	Machine Learning
MR	Main Radio
NLOS	Non-Line-Of-Sight
OLOS	Obstructed Line-Of-Sight
PoI	Points of Interest
QoS	Quality of Service
RF	Radiofrequency
RNG	Relative Neighborhood Graph
Rx	Reception
Tx	Transmission
UAV	Unmanned Aerial Vehicle
VoS	Value of Sensing
WN	Wireless Network
WSN(s)	Wireless Sensor Network(s)
WuC	Wake-up Call
WuR	Wake-up Radio

Wireless Sensor Networks

This section presents some concepts and fundamentals related to WSNs. The intention is not to delve deeper into the matters covered but to provide the basics to support a better understanding of the primary topics inherent to the works in our systematic review.

A WSN (Fig. 1) comprises devices (sensor nodes) with sensing and actuation capabilities connected through wireless communication (El Khediri, 2022; Rawat *et al.*, 2014). The network can be self-organizing or infrastructure-based. In the former case, it resembles MANETs in the most fundamental matters. In the latter situation, an entity (e.g., sink node) coordinates sensor nodes. Most WSNs' applications have the purpose of monitoring an environmental phenomenon: Nodes gather data (e.g., temperature, humidity, luminosity), possibly perform some local data processing, and send them to a local or remote destination, conceivably using the Internet (Kandris *et al.*, 2020).

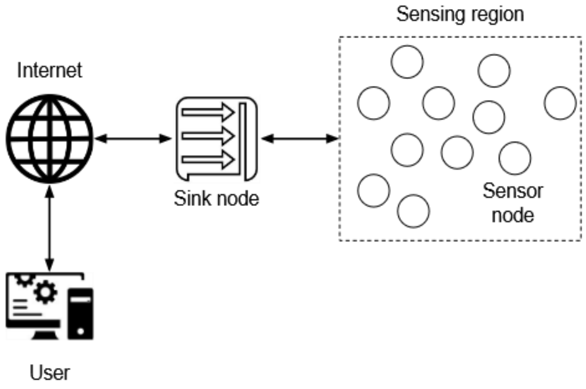


Fig. 1: Typical elements in a wireless sensor network.

Sensor node deployment is the foremost problem in WSNs. Nodes' locations depend on covering requirements and monitoring events. Static (offline) node placement lets one choose where each node must stay (i.e., PoI coverage). Online placement assumes at least some nodes have mobility capabilities, allowing topology adjustments to cope with any coverage and connectivity issues. When event monitoring mandates fault tolerance, the main QoS criteria is the PoI's connectivity reliability.

Erdelj *et al*. (2011) address the problem of mobile sensor deployment for PoI coverage, assuming that nodes initially have a communication link with a base station. The authors propose a distributed algorithm that uses local information (i.e., a subset of neighbors) and virtual forces to steer the sensors' movement. The proposed algorithm explores the concept and the properties of Relative Neighborhood Graphs (RNG), letting nodes autonomously move toward the PoI while ensuring communication constraints. They show that their solution achieves near-optimal coverage and connectivity performance with low communication and computation overhead.

Tarnaris *et al*. (2020) present a solution for the coverage and k-coverage (i.e., at least k nodes must cover each PoI) optimization problem in WSNs. Their solution applies two computational intelligence methods: Genetic algorithm and particle swarm optimization. The paper evaluates the performance of the methods in terms of coverage ratio. For the k-coverage requirement, case studies define the corresponding set of target spots. The work employs statistical testing to evaluate the methods, demonstrating that they are close to the ideal solution. However, the evaluation does not consider connectivity, energy consumption, and other crucial network performance metrics.

Adday *et al*. (2019) surveyed several deployment techniques for WSNs, classifying them as computational geometry-based, force-based, grid-based, and metaheuristic-based. The paper analyzes their impact on network performance, such as coverage, connectivity, and fault tolerance. In addition, the work lists some practical challenges and research problems in WSN deployment. They emphasize that most deployment proposals address coverage and connectivity based on ideal conditions, such as nodes having uniform radio ranges and no physical obstacles. Any realistic deployment approach should consider power consumption, accuracy, reliability, and scalability. Even though solutions are addressing some of these particular metrics, there is a need for more realistic approaches.

Chang *et al.* (2020) propose a path-planning scheme for wireless sensor networks with mobile sinks. These nodes enhance the data-gathering process by moving to the sensing area. The scheme employs an angle bisector notion to produce the moving path for the mobile sink, accounting for the existing obstacles. This lowers the moving distance and extends the lifetime of the mobile sink. The scheme is validated by simulation, showing that it outperforms a formerly designed greedy-based solution regarding the moving distance.

Tossa *et al*. (2022) tackle the dual problem of maximizing the area coverage and guaranteeing the connectivity of sensor nodes in WSNs. The paper proposes an analytical model and a complex objective function for the problem and solves it using a genetic algorithm. Their algorithm solves the problem of covering any area with a predefined number of sensors, finding the best positions to maximize the coverage while guaranteeing connectivity. Although the solution considers any area format, they assume homogeneous nodes (i.e., same processing and communication capacity) with ideal transmission and reception range (i.e., circular radio coverage area), and obstacles are only indirectly present through the concept of areas of no interest. However, their solution can be a practical tool for computing the required number of sensors with guaranteed connectivity under a given coverage constraint.

Deepa and Revathi (2023) study the problem of efficient target monitoring with fault-tolerant connectivity in WSNs. Their solution starts by defining clusters of nodes (based on the Set Cover concept) around each PoI, aiming for an extended network lifetime. A nature-inspired algorithm (i.e., moth flame optimization) is the basis for placing an optimal number of nodes among the disjoint sets. The nodes form a backbone sustaining a fault-tolerant connection to the sinks. The authors evaluate the work through simulations based on a custom simulator, showing that their solution outperforms other solutions regarding network lifetime. Results are inconclusive because the evaluations focus primarily on the algorithmic aspects of the coverage and the fault-tolerance connectivity to the sinks. However, the algorithm allows computing an estimate for the minimum number of sensors to meet the fault tolerance criteria for a given scenario.

Wake-up Radios

This section follows a similar path to that taken for WSNs. It delivers the basics supporting WuRs while addressing two fundamental aspects. First, there is a potential demand for WuR technologies in the face of established practices (e.g., those based on duty cycles and scheduled sleeping states). Second, it provides a synopsis of the various WuR approaches currently available in the literature. To help better understand these and other related elements, we present our taxonomy for WuR devices.

WuR-based WSNs vs. Traditional WSNs

Many WSN MAC protocols follow a design that considers the possibility of waking up nodes that are typically inactive most of the time. For instance, Zheng *et al.* (2005) proposed the Pattern-MAC (PMAC) protocol that allows a WSN node to have adaptive sleep-wakeup schedules based on the duty cycles. When comparing an approach such as that to the WuR options in terms of energy efficiency, we may consider three aspects: (a) the application's duty cycle, (b) whether the application is delay tolerant (e.g., latencies on the order of seconds) and (c) if the application requires on-demand responses from the sensor nodes. We consider these three aspects next.

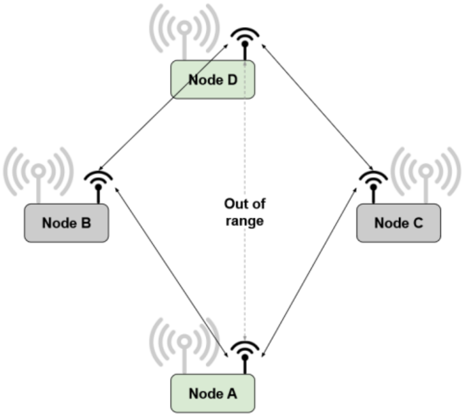
Kozłowski and Sosnowski (2019) investigated the tradeoffs between WuR and regular WSNs under different duty cycles. When nodes are usually sleeping, duty cycle scheduling approaches are usually preferable. However, in such cases, waking a node from its deep sleep is not an option. In other words, when energy efficiency and on-demand activation of sensor nodes are required, WuR solutions are a compelling alternative (Da Silva *et al*., 2019).

As a side effect, the impact of WuRs' on the system's latency results from:

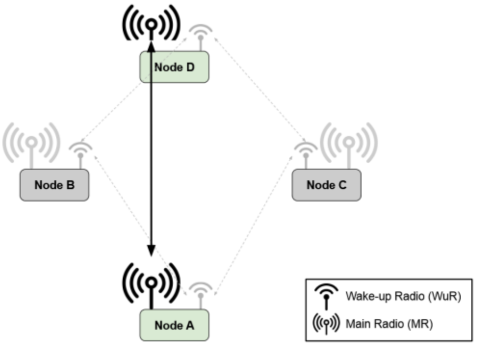
1. When using passive WuR receivers, RF (or similar) harvesting imposes a non-negligible delay in getting the node ready for activation, sensing, and data communication
2. When a regular WSN radio is used as part of the WuR receiver, the sleeping energy is significantly reduced by applying a duty cycle to the radio. Therefore, the maximum period during which the radio can be regularly powered off or maintained in an inactive state also imposes additional latency on the WuR solution
3. When adopting self-organizing WSN protocols, there is an additional latency to accomplish the network wake-up

The adoption of WuR technologies in WSNs allows for a myriad of network architectures. In one extreme, a simple architecture involves dedicating the WuR-Tx role to a single node with enough transmit power to wake all nodes up. This architecture is likely a good fit for scenarios where the sink node can autonomously infer when the WSN must start its sensing data collection. On the other hand, when we want to wake nodes up selectively, such an approach is unsuitable because it may result in many undesirable wake-ups and, consequently, wasted energy.

The usual situation is maintaining a shorter radio range when operating with the WuR (Fig. 2), resulting from a lower power transmission than the Main Radio (MR). In this architecture, the wake-up process occurs progressively as each node wakes its nearby neighbors, eventually reaching the target nodes after several retransmissions. This approach follows the energy savings guidelines, aiming at extending the system's lifetime while being subject to additional latency, as discussed before. Complementarily, by diminishing the WuR transmission power, one expects to lower the number of nodes woken up unintentionally (i.e., on average, a node's neighborhood within the WuR range is smaller than the one resulting from the MR range). Furthermore, it is not unusual to have low-power radios (e.g., Texas Instruments™ CC2652R) showing similar transmission and reception consumption (CC2652R7, 2023). Hence, shorter WuR ranges can potentially impact energy savings on both endpoints (i.e., transmitter and receiver).



(a) Radio range during WuR activation



(b) Communication range with the MR after wake-up

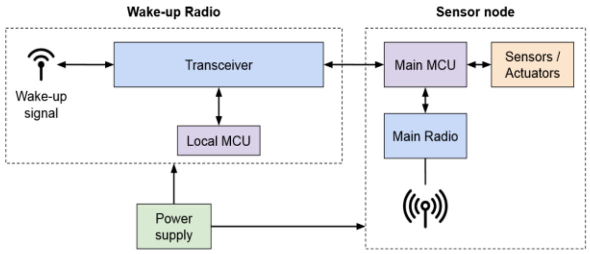
Fig. 2: A typical out-of-band WuR scenario: (a) radio range assuming the WuR, and (b) with the MR after waking up

A Taxonomy for WuR Devices

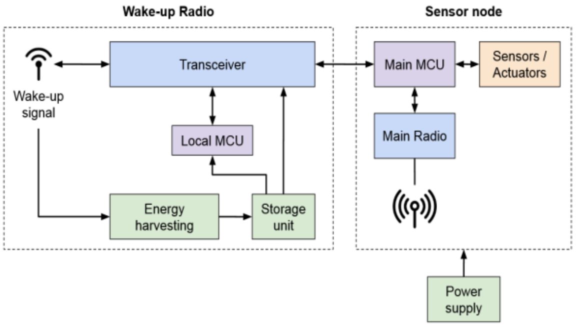
One of the main challenges while reviewing WuR-related works applied to WSNs concerns the broad scope of potential technologies for successfully waking a node, including possibilities other than those using Radio Frequency (RF). For instance, one can use acoustic waves (or infrared or magnetic induction) as the core technology for the devices with the single goal of waking nodes up. That is an example of an out-of-band strategy because we employ distinct technologies. On the other hand, if both WuR and MR devices use the same RF (typically ISM bands), it is not necessarily an in-band approach. For instance, even though Da Silva *et al.* (2019) employed two different radios with the same ISM band, their solution is deemed out-of-band because one radio assumes the WuR role while another performs regular data communication.

A WuR device can either Transmit (Tx) or Receive (Rx) a Wake-up Call (WuC), or both. The devices also differ in how they are powered: Using energy from batteries or harvested energy. As briefly described in the first section, there are roughly two variants of WuRs: Active and passive (Fig. 3). In the active mode, the WuR-Rx device remains continuously listening. In contrast, the other device's components stay inactive (i.e., completely turned off or deep asleep). Thus, the WuR-Rx needs a constant power supply to support listening and analyzing a wake-up signal, which, depending on the characteristics of the process (e.g., broadcast or address-based), requires the support of a Microcontroller Unit (MCU). The passive mode differs throughout the wake-up procedure, as the WuR-Rx also stays inactive like the remaining system's components. In this configuration, we must adopt a mechanism for capturing energy from the radio frequency signal emanating from the transmission source (i.e., the origin of the wake-up signal). The capacity to capture this energy is directly related to the transmission power of the WuR-Tx device and inversely proportional to the square of the distance between the source (WuR-Tx) and the receiver (Wur-Rx) (Friis, 1946). Therefore, as the distance between them increases, the time required to capture the minimum necessary energy to reactivate the WuR unit and process the wake-up signal rises.

In a standard WuR, address decoding is usually a task for a dedicated microcontroller. While not processing a WuC, the microcontroller can stay deep asleep. For low data rate scenarios, Ziesmann *et al.* (2023) show that it saves power by completely switching off the microcontroller while the WuR is just listening. They state that deep-sleep state modes can be overrated, not only for WuRs. An addressing mechanism can target a single node (unicast), a subset of nodes (multicast), or all nodes (broadcast). An ideal solution provides all these options.



(a) Active Wake-up Radio



(b) Passive Wake-up Radio

Fig. 3: Out-of-band WuR solutions: Active (3a) and passive (3b) WuR nodes. A wake-up signal triggers the WuR, eventually initiating the main MCU and the MR. Typically, a passive WuR is more energy-efficient than an active one at the expense of being feasible only for short distances (i.e., just a few meters).

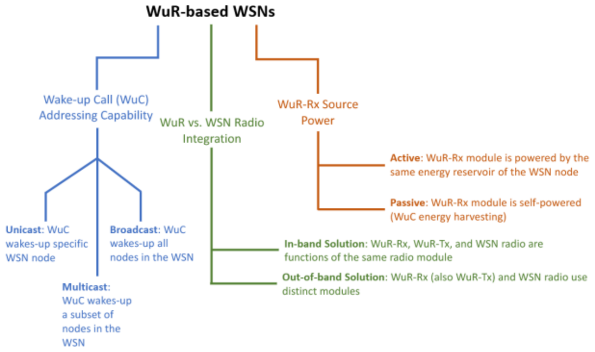


Fig. 4: A taxonomy for WuRs applied to WSNs.

Da Silva *et al*. (2019) propose address matching in the analog domain with no symbol decoding: To match, the wake-up call continuous wave frequency must correspond to the one pre-configured at the receiving WuR. In addition, the receivers have filters configured with non-traditional bandwidth, resulting in a more efficient wake-up signal detection mechanism. Based on empirical results from five outdoor networks operating in harsh conditions, they show that their solution works for distances longer than 200 m with no false positives. However, longer distances come at the expense of more prolonged wake-up delays, mainly when the WuR solution is adopted outdoors.

Fig. (4) summarizes the different aspects associated with the diversity of WuR solutions applied to WSNs. This taxonomy is relatively superficial and does not capture all the differences between the variants in our systematic review. Nonetheless, it highlights the potential complexity levels of a WSN employing WuRs.

Methodology

We perform a systematic review of WuR applied to WSNs. We begin by formulating the research questions, from which we infer the results we intend to obtain from the review. We have defined the following research questions:

- RQ1: What are the works' research topics and their main results?
- RQ2: What roles do WuRs play in the research problems?
- RQ3: What are the works' main limitations?
- RQ4: What are the open problems?

Exclusion and Inclusion Criteria

Our approach to filtering studies is rigorous and meticulous. We have defined essential criteria for including and excluding papers, ensuring our review is comprehensive and focused. Let's examine these criteria more closely.

The inclusion criteria are papers published in English within the last ten years (i.e., 2014-2024). A ten-year timespan is adequate for getting acquainted with our research topic's state of the art, considering the most recent works surpass or confirm the previous ones. Complying with the inclusion criteria is easily doable through each publisher's search engine.

The exclusion criteria are overlapping papers and papers in which WuRs play a minor role in the research problem addressed in WSN. While the first is easy to fulfill, the second requires manually checking each work. We want to focus only on works that strictly count on WuRs in the research problem addressed in WSNs.

Repositories

As researchers and professionals, we understand the importance of rigorous scientific methods and trusted publishers in ensuring the reliability and validity of our findings. Therefore, we have considered only works that follow the scientific method as their primary foundation and are published by globally recognized publishers (e.g., Science Publications, ACM, IEEE, MDPI, ScienceDirect, and Springer).

Search String

To limit the search string, we emphasize the keywords "wake-up radio" and "wireless sensor network". To compile a list of works restricted to such subjects, we define the search string as [“wake-up radio” AND “wireless sensor network”].

Literature Review and Results

After searching each Publisher’s Digital Library and applying the inclusion and exclusion criteria, we have 30 papers: 21 journal papers and nine conference papers. Table (2) presents the paper selection distribution concerning their publishers. This section blends the literature review and the research results to make the process direct and concise.

RQ1: What are the Works’ Research Topics and their Main Results?

Most works focus on improving the network lifetime while balancing energy consumption and other performance metrics (e.g., connectivity reliability, latency, and coverage requirements). Table (3) lists the works’ primary research topics and briefly describes their main contributions.

Physical and MAC

Works dealing with physical and MAC focus on tuning or adding new features to the WuR to support enhanced MAC operations.

Da Silva *et al*. (2019) propose a solution for enhancing WuR communication reliability (i.e., no false positives) for more considerable distances under heavy RF interference for both Non-Line-Of-Sight (NLOS) and Obstructed Line-Of-Sight (OLOS) conditions. The WuR addressing scheme is based on the WuC continuous wave signal frequency and requires no additional processing. Receivers have filters configured with non-traditional bandwidth and a more sensitive wake-up signal detection mechanism. The validation employs two years of monitoring data from several deployments of outdoor WSNs. Results show that the proposed framework can provide reliable communication for distances larger than 200 m. However, more considerable distances come with longer wake-up delays.

Chen *et al*. (2015) propose improvements to extend the activation range for passive WuRs. The design introduces two energy-efficient features: An improved energy harvester circuit and an enhanced MCU triggering mechanism for handling WuCs. A real testbed is presented and evaluated.

Table 2: Publishers’ search results: Number of papers after applying inclusion and exclusion criteria

Publisher	Number of papers
IEEE	12
ScienceDirect	8
ACM	6 (one paper is a joint publication with IEEE)
Springer	2
MDPI	2

Table 3: Work’s research topics and main contributions

Research topic	Main contributions
Physical and MAC (Da Silva *et al*., 2019; Chen *et al*., 2015; Petrioli *et al*., 2014)	• Improved wake-up distances • Selective wake-ups (e.g., enhanced addressing mechanisms) • Improved energy harvesting mechanism for WuRs • Early data transmission (i.e., small data payload within wake-up signaling)
MAC (Ali *et al*., 2020; Ghose *et al*., 2018; 2019; Ait Aoudia *et al*., 2018; El Hoda Djidi *et al*., 2018; Kazdaridis *et al*., 2017; Jelicic *et al*., 2014; Magno *et al*., 2014)	• Most solutions assume star topologies, without routing • WuRs make transitioning between asynchronous and duty-cycling communication • Nodes' residual energy is a good metric to improve waking-up criteria • WuRs improve the energy efficiency of surveillance applications
MAC and routing (El Hoda Djidi *et al*., 2022; Huang *et al*., 2021; Sampayo *et al*., 2021; Singh and Sikdar, 2020; Trotta *et al*., 2020; Pegatoquet *et al*., 2019; Sutton *et al*., 2019; Piyare *et al*., 2018; Aouabed *et al*., 2022; Liu *et al*., 2024)	• On-demand routing load balance is shown feasible through auxiliary nodes equipped with WuR • Clustering routing benefits from asynchronous node activation using WuRs • UAVs coordinate ground node asynchronous activation through WuRs • Hybrid solutions, leveraging synchronous (contention-free) and asynchronous communications with WuRs
MAC and localization (Niculescu *et al*., 2022)	• Localization of ground nodes based on asynchronous node activation and exchanging ranging transmissions
Content-based polling (Shiraishi *et al*., 2023)	• Wake-up decision based on range interval of sensor readings and accuracy
Broadcasting (Bannoura *et al*., 2015; Sutton *et al*., 2015)	• Minimizing the number of wake-up calls during broadcast transmissions • Simultaneous broadcast transmissions with little or no interference
Cross-layer communication (Aranda *et al*., 2020; Boubiche *et al*., 2015)	• Cross-layer tunning for regular and emergency events • On-demand WuR node activation based on physical, link, and routing layer interactions
Prototyping (Cabarcas *et al*., 2020)	• An open prototyping platform for designing applications using WuRs, providing precise power monitoring
Energy modeling (Aranda *et al*., 2018)	• Present an energy model for estimating energy consumption on WSNs based on WuRs
A case advocating for WuRs in WSNs (Oller *et al*., 2016)	• Several realistic WSN scenarios are extensively evaluated, showing that WuRs deliver a genuine performance leap compared to the most used duty cycle protocols

The results include extensive simulations (in Matlab) comparing the proposed solution with other passive and active radios and a duty cycle protocol. They show that the proposed solution outperforms the others in network lifetime, latency, and packet delivery ratio.

Petrioli *et al*. (2014) designed a wake-up receiver architecture combining frequency-domain and time-domain addressing space for selectively identifying nodes (i.e., nodes may have multiple IDs). The solution supports a wake-up-enabled harvesting-aware communication stack that supports interest dissemination (i.e., commands from the sink to the sensor nodes) and converges casting (from all sensor nodes to the sink). A prototype and extensive simulation results show that the proposed architecture and protocol stack outperform other duty cycle protocols, exploring latency and network lifetime tradeoffs.

Ghose *et al.* (2019) introduce two improvements to the processing time and energy efficiency of WuCs: Early Sleep (ES) and Early Data Transmission (EDT). ES reduces the processing time during overhearing: If no address matches, go back to sleep earlier. Besides having the destination address, EDT uses the WuC transmission to piggyback a small payload of 10 bits, with and without ACKs. ES and EDT are mutually exclusive because EDT requires overhearing. Validation of the basic mechanisms employs a real testbed, and analytical and simulation (Matlab) performance results show that improvements occur mainly in low data rate scenarios. Total overhearing energy consumption improves primarily in scenarios with a more significant number of nodes. EDT reduces latencies because the WuR can process the data before waking the main radio. EDT without ACK reduces delays compared to EDT with ACK because the MR needs to wake up to send ACKs.

Kazdaridis *et al*. (2017) present a WuR prototype based on LoRa's long-range technology. The solution includes a power-efficient microcontroller that supports selective wake-ups based on destination address decoding. A testbed validates a single node, which consumes around 700 nA in the listening state and 1.8 µA during the active state.

MAC

Most MAC solutions under consideration do not assume an associated routing protocol because they usually presume star topologies. However, direct communication (i.e., one-hop) remains functional even if paths over WuR links are multi-hop.

Ali *et al.* (2020) designed an asynchronous duty-cycle MAC protocol, with sink nodes sleeping until they awake through their WuRs. Monitoring sensor activity allows dynamically setting the duty cycle (i.e., so that the sink can receive sensor data), resulting in less energy consumption. Simulation results (COOJA simulator) show good performance improvements for low data traffic.

Ait Aoudia *et al.* (2018) propose a MAC protocol leveraging energy harvesting and WuRs. In the wake-up signal, the sink informs the sequence number of the next packet expected from the corresponding sensor node. Based on the analytical analysis and an actual hardware implementation tested in real scenarios with star topologies, the protocol outperforms two state-of-the-art MAC protocols, achieving a 2.5 gain in throughput.

El Hoda Djidi *et al*. (2018) propose an energy-efficient MAC protocol leveraged on WuRs, assuming that nodes know other nodes' residual energy. Transmission can be direct (one hop) or through relayers, choosing the one that minimizes energy costs. Upon receiving a CTS, a node's backoff time is shorter for more considerable residual energies (hence, the node with the most significant residual energy becomes the relayer). A node sends an About to Send (ATS) message before transmitting a data packet. If the source decides to send directly, it sends an ATS instructing the other nodes not to relay. The work describes a prototype as a proof of concept, and performance evaluations with analytical models and micro-benchmarks show a lifetime gain of up to 1.7 when using two relayers.

Ghose *et al.* (2018) propose three MAC protocols suited for different traffic patterns, assuming event-driven WSNs with star topologies. The solutions explore Clear Channel Assessment (CCA), back off plus CCA, and adaptive WuC transmissions. The protocols' performance analysis uses an analytical framework based on M/G/1/2 queues and discrete-event simulations to validate the analytical model's accuracy. Results show that the protocols outperform a reference MAC protocol in energy consumption and WuC losses but perform worse in packet latency.

Jelicic *et al.* (2014) propose a two-tier (multimodal) surveillance WSN framework with WuR as the primary tracking activation mechanism. Infrared sensors track user presence, activating camera devices through WuR communication. Analytical analysis and Matlab simulations show that the proposed solution is more energy efficient and faster than duty cycle approaches (two orders of magnitude lower latency).

Magno *et al.* (2014) designed an energy-efficient overlay surveillance WSN leveraged on ultra-low power infrared sensor nodes and WuRs. Infrared presence detection triggers the activation, via WuRs, of power-intensive nodes (e.g., cameras). Using simulations and actual deployment, they show that the proposed solution extends the network lifetime compared to other approaches.

MAC and Routing

Liu *et al.* (2024) present a routing solution in WSNs that supports differentiated services (i.e., regular and urgent data) with guaranteed low latency and efficient energy consumption. With the intent to reduce the network deployment cost, only part of the nodes have WuRs. Their activation happens in a coordinated manner and only occurs when regular nodes (i.e., without WuRs) cannot handle the momentary transmission demand. The auxiliary nodes are activated to meet the transient demand and then return to the sleeping state. The solution guarantees a minimum number of nodes equipped with WuR, thus reducing network deployment costs while ensuring urgent data transmission.

Aouabed *et al*. (2022) present a solution for multi-hop (WuR range) clustering in single-hop (MR range) networks. Multi-hop path selection uses nodes' residual energy and distance to Cluster Heads (CHs). On-demand WuR node activation reduces power consumption. Simulations with Matlab show the clustering solution outperforming two representative protocols, improving network lifetime and packet delivery (no results regarding latency).

Huang *et al.* (2021) propose decision criteria for a sensor node relaying packets in a multi-level WSN with a single sink (tree topology). Nodes accumulate packets during a maximum waiting time, then start burst transmission, aiming to reduce collisions. Theoretical analysis and simulation-based experiments via Matlab compare the relaying approach to a basic tree-forwarding scheme. Results point to promising performance improvements.

Sampayo *et al.* (2021) propose a routing protocol leveraging WuRs to establish a wake-up procedure between source and destination. Once the destination wakes, they can communicate using a single hop link employing the MR. The waking-up procedure also includes a load-balancing mechanism to leverage the multiple paths between source and destination. The work describes extensive simulations using the COOJA simulator. Results show that the routing solution allows up to 300% network lifetime improvements compared to duty cycle approaches.

Singh and Sikdar (2020) designed a receiver-initiated broadcast-based MAC protocol and a clustering approach to reduce contention. The work describes a theoretical basis for defining the optimal number of groups. The protocol is validated using a Markov chain model. The results show that the protocol performed superiorly compared to other protocols.

Trotta *et al*. (2020) developed a data-gathering solution based on multiple UAVs acting as mobile sinks with the assistance of charging stations. The protocol computes the UAVs' paths following a distributed or centralized approach. Quality of sensing data (Value of Sensing, VoS) works as a metric to distribute the load evenly among ground sensors, which the UAVs awake as they hover over the ground. The optimization framework considers the lifetime of ground sensors, UAV energy constraints, and VoS. The solution maximizes VoS when compared to greedy path-planning. They present theoretical analysis and simulations based on the OMNeT++ simulator. Results show a lifetime enhancement of up to 30%

Pegatoquet *et al.* (2019) designed a MAC protocol for autonomous WSNs leveraging WuRs. The base station (BS/sink) has a permanent energy source, while sensor nodes harvest their energy. A neighbor discovery algorithm lets nodes build a forwarding table for wake-up calls. WuR and MR use the same frequency but transmit at different rates. WuCs are transmitted only with the MR and may traverse several hops until reaching the destination. After that, the destination transmits to the BS in a single hop using the MR. As a proof of concept, the work describes a prototype for indoor monitoring (with sensors harvesting power from indoor light). OMNeT++ simulation results show that the proposed protocol outperforms the state-of-the-art duty-cycle approaches regarding energy, latency, and collisions.

Sutton *et al.* (2019) proposed an architecture leveraging synchronous (via allocation of small contention-free slots) and asynchronous (via WuR) flooding communication in multi-hop event-driven WSNs. The solution also provides mechanisms to reduce false positive wake-ups. They present a proof of concept based on an indoor testbed. Performance results show improvements in terms of latency and energy consumption.

Piyare *et al.* (2018) combine long-range and short-range transmissions for asynchronous communication (TDMA + LoRa) into a network architecture based on two-hop topologies with clustering (sink, cluster heads, and end nodes). The protocol is receiver-initiated: The sink starts by requesting a CH to wake up its cluster members. End nodes send data directly to the sink via LoRa, following a schedule defined by the sink (avoiding collisions). In addition, the architecture overcomes some of the LoRa Wide Area Network.

(LoRaWAN) (LoRa Alliance, 2024) limitations include its inability to communicate on-demand with end devices. The work describes an indoor testbed with 11 sensors for validation: Nine end nodes, one CH, and one sink. Preliminary results show that the solution is scalable and energy-efficient, and it can achieve 100% reliability. The work estimates a three-year lifetime for the testbed, assuming nodes use low-capacity batteries.

MAC and Localization

Niculescu *et al*. (2022) present a solution for the localization in 2D of random nodes in a WSN. A UAV starts the scanning by sending wake-up beacons to the destination node. After exchanging ranging transmissions, the UAV gets several way-point measures to infer the node's location, and data transmission begins once the UAV locates it. Validation happens using synthetic data and a real flying drone. The results show sub-meter precision and a node's energy consumption 800 times smaller than realistic duty-cycle approaches, but the UAV energy consumption is not further analyzed. Reasonable precision measures are possible when UAV height is between 5 and 20 m.

Content-Based Polling

Shiraishi *et al.* (2023) proposed a solution for content-based wake-up (CoWu): Sensor readings are helpful only if they comply with the requested criteria (range interval) and can reach the sink node before the deadline (accuracy). Numerical results show enhanced accuracy and better energy efficiency than a round-robin approach.

Broadcasting

Bannoura *et al.* (2015) present theoretical and practical results for the on-demand activation of a connected, energy-efficient dominant set, aiming to wake up a large set of sensor nodes via WuR. The proposed solution minimizes the number of wake-up signals transmitted to increase coverage and reduce energy consumption. Different variants of the proposed algorithms are simulated in a custom simulator, showing that it can reach nearly all nodes with a small number of wake-up calls. A comparison between the simulated algorithms shows the benefit of the generated knowledge over no prior knowledge. The authors claim that this raises the hope that duty-cycling might soon be a technique of the past.

Sutton *et al.* (2015) present an energy-efficient protocol for on-demand flooding of rare events in multi-hop WSNs. A node awakes neighboring nodes asynchronously (via WuRs) to communicate synchronously afterward. They employ carrier frequency randomization to support multiple simultaneous transmissions with little or no interference, which could benefit dense scenarios. The work describes an evaluation in a controlled laboratory setting and an indoor testbed.

Cross-Layer

Aranda *et al.* (2020) proposed a coss-layer framework for reliable and energy-efficient communication in multimodal WSNs. On-demand node activation allows for reducing latency and increases packet delivery ratio. The cross-layer interactions allow the proper tuning for regular and emergency events. They use an indoor proof of concept with four sensors and one sink for the validation. The proposed solution shows reduced latency and a better packet delivery ratio than a single-radio system.

Boubiche *et al.* (2015) present a cross-layer approach following a non-traditional interaction model between layers, letting the network layer inform the physical layer about the transmission power applied when talking to each neighboring node. Likewise, the link layer receives information from the network layer that allows it to coordinate, together with the physical layer, the activation of neighboring nodes via WuR. The result is a hierarchical (cluster-based) energy-efficient routing solution. They run simulations on NS2 for validation, and the results show better energy savings, network lifetime, packet delivery ratio, and end-to-end delay.

Prototyping

Cabarcas *et al*. (2020) present a platform based on open software and COTS hardware components for prototyping WSN applications with WuR capabilities. A module unit allows precise power monitoring for the WuR module and the sensor node. Based on a real network with a linear topology, they show how to measure power consumption and latency.

Energy Modeling

Aranda *et al.* (2018) present an energy model for estimating energy savings on WSNs based on WuRs. The model captures the impact of employing specific WuR capabilities (e.g., addressing), assuming in-band WuRs and multi-hop networks. It is validated based on analytical results for various network scenarios. It shows that WuRs can significantly extend the network lifetime in multi-hop networks with short event periods compared to low-duty cycle approaches.

A Case Advocating for WuRs

Based on actual hardware specifications and a representative network simulator (OMNET++) with the proper features for seamless simulation of WuRs, Oller *et al*. (2016) compare the most representative duty cycle protocols with their protocol based on WuRs. The proposed simulation environment extensively evaluates several realistic WSN scenarios, showing that WuRs deliver a genuine performance leap compared to standard duty cycle approaches.

RQ2: What Roles Do WuRs Play in the Research Problems?

The WuR is key in activating sensor nodes on demand and enabling asynchronous communication. The radio unit can react to the wake-up signaling in the following ways:

- Waking up indiscriminately: When there is no addressing mechanism, the WuR triggers the wake-up process as soon as it receives the wake-up signal (broadcast mode)
- Waking up selectively:
  - Based on some addressing mechanisms, including allowing the device to have multiple addresses and letting only the radio(s) with the destination address(es) proceed with the activation process,
  - Based on some flagging criteria, activation signaling includes parameters such as range limits. It wakes a node only if its retained data is not outdated and meets the requested criteria.

This selective waking-up process is a crucial feature of WuRs

The waking-up signaling can initiate at the destination (i.e., sink node) and be periodic or on-demand, showcasing the adaptability of WuRs in various scenarios. The targets can be all end nodes, a subset of them, or a particular destination. Reaching the intended targets requires broadcasting unless a forwarding path is available (e.g., provided by the upper layers). Otherwise, the signaling can be event-driven, starting at the end nodes and converging at the sink node (converge cast). When mobile nodes are present (e.g., UAVs), usually as data mules, WuRs enable the synchronization between the mobile node and the ground nodes, further demonstrating their versatility.

Most works assume a star topology when communicating through the MR. However, due to their shorter radio ranges, we usually have a multi-hop network when intercommunicating via the WuRs. Therefore, the waking-up signaling takes place over a more complex topology. Some solutions reduce false positives and contention by resorting to selective transmissions based on forwarding tables, backbone structures (e.g., based on graph domination concepts), or local decision techniques (e.g., backing off time inversely proportional to the nodes' remaining energy). Once the target peers (i.e., source and destination) are active, the WuRs facilitate direct communication via the MR (i.e., single-hop communication), underscoring their crucial role in the system.

RQ3: What are the Works' Main Limitations?

The research's findings and conclusions, which are deeply rooted in their underlying premises, testify to the complexity of our analysis. It is crucial to underscore that our understanding builds upon these intricate assumptions and their far-reaching implications. Table (4) summarizes the work's main limitations.

The application of WuRs in WSNs has its challenges. Specific characteristics of WuRs, regardless of other system features, can hinder their effectiveness. For instance, using broadcast-based wake-ups can lead to false positives, a problem that intensifies in more extensive and denser networks. The reduced radio range can also pose connectivity issues, often requiring more sensor nodes. Therefore, any WSN design that incorporates WuRs must carefully navigate these challenges.

While there are challenges, most studies support the use of WuRs to enhance power management, particularly in low-data-rate scenarios, which is a significant finding emphasizing WuRs' potential benefits. However, frequent waking-ups can significantly increase energy consumption in higher data-rate scenarios. At a certain point, alternative approaches, such as duty cycling, may be more viable.

Modeling or simulation restrictions narrow analysis in some works, such as in the following situations:

- Analytical modeling overlooks the essential layers: Physical (Aouabed *et al*., 2022) or physical and link (Huang *et al*., 2021)
- Simplistic channel modeling: Error-free transmissions (Shiraishi *et al.*, 2023; Singh and Sikdar, 2020; Aranda *et al*., 2018), an infinite retransmission limit (Singh and Sikdar, 2020), or interference effects ignored (Ghose *et al*., 2019)
- Routing overhead is disregarded (routing tables computed offline) (El Hoda Djidi *et al*., 2022)
- Assuming only in-band WuRs with the same radio range as the MR (Aranda *et al*., 2018)

Some limitations relate to the system/protocol design or simulation settings, such as the following:

- There is no wake-up addressing mechanism (e.g., broadcast mode), which makes it more prone to false positives (Liu *et al*., 2024; Aranda *et al*., 2020; Chen *et al*., 2015; Sutton *et al*., 2015)
- Node localization is restricted to 2D, assuming line of sight (Niculescu *et al*., 2022)
- Information regarding sensor node deployment/location is considered a prerequisite (Trotta *et al*., 2020)
- Passive WuRs limit the distance between neighboring nodes (Trotta *et al*., 2020)
- Restricted data traffic settings (e.g., uniform packet rate and size) (Ali *et al*., 2020)
- Support only WSNs with a single sink (Aouabed *et al*., 2022; Pegatoquet *et al*., 2019; Ait Aoudia *et al*., 2018)
- Strictly limited evaluation scenarios: routing evaluation with just two relayers (El Hoda Djidi *et al*., 2018), clustering evaluation with a few nodes in a single cluster (Piyare *et al*., 2018), and the validation relying on a single node (Kazdaridis *et al*., 2017)
- Incorporating new WuR technologies might be a limiting factor with prototyping platforms (Cabarcas *et al*., 2020)

RQ4: What are the Open Problems?

Several works (Aranda *et al*., 2018; 2020; Cabarcas *et al*., 2020; Singh and Sikdar, 2020; Trotta *et al*., 2020; Ghose *et al*., 2018; 2019; Pegatoquet *et al*., 2019; Kazdaridis *et al*., 2017) deem as appropriate the need for more extensive evaluation scenarios, especially when it comes to augmenting simulations' capabilities. Therefore, more realistic stack layers (e.g., physical and network layers) are needed to improve insights into the impact of the underlying protocols (e.g., channel interference, routing control overhead) on systems' performance.

Table 4: Work's main limitations

Limitation roots	Critique
Modeling or simulation restrictions	• Physical (Aouabed *et al*., 2022), or physical and link (Huang *et al*., 2021), simple modeling makes a more realistic analysis difficult. Specifically, the following restrictions may blur the performance results and analysis: error-free transmissions (Shiraishi *et al*., 2023; Singh and Sikdar, 2020; Aranda *et al*., 2018), an infinite retransmission limit (Singh and Sikdar, 2020), or interference effects ignored (Ghose *et al*., 2019) • Computing routing tables offline (El Hoda Djidi *et al*., 2022) completely disregards the routing overhead during the system's lifetime • When one assumes only in-band WuRs with the same radio range as the MR (Aranda *et al*., 2018), the solution defeats the purpose of producing a more energy-efficient solution
System design or simulation settings	• No wake-up addressing mechanism (i.e., broadcast mode) (Liu *et al*., 2024; Aranda *et al*., 2020; Chen *et al*., 2015; Sutton *et al*., 2015) increases occurrences of false positives, which may even cancel out the energy saving advantages made possible by asynchronous activation based on WuRs • When present, node localization triggered by WuRs is restricted to 2D assuming line of sight (Niculescu *et al*., 2022), which can be a limiting factor in most scenarios • Sensor nodes' deployment location as a prerequisite (Trotta *et al*., 2020) might not be feasible in most circumstances • Restricting the application exclusively of passive WuRs (Trotta *et al*., 2020) might require a too large number of devices due to their limiting activation range • When restricting the data traffic settings (e.g., uniform packet rate and size) (Ali *et al*., 2020), it does not capture the characteristics of most realistic WSN scenarios • By supporting only WSNs with a single sink (Aouabed *et al*., 2022; Pegatoquet *et al*., 2019; Ait Aoudia *et al*., 2018), the works ignore some important scalability concerns • Strictly limited evaluation scenarios: routing evaluation with just two relayers (El Hoda Djidi *et al*., 2018), clustering evaluation with a few nodes in a single cluster (Piyare *et al*., 2018), and the validation relying on a single node (Kazdaridis *et al*., 2017) • Incorporation of new WuR technologies might be a limiting factor with prototyping platforms (Cabarcas *et al*., 2020)

Among the most prominent future works, there are the following (Table 5 summarizes the list):

- Explore management options for prioritizing data transmissions during emergencies, support handling dead nodes, and allow dual switching between channel access modes (Aranda *et al*., 2020)
- Explore multi-objective optimization methods for clustering of nodes (Aouabed *et al*., 2022)
- Research energy-efficient network coding techniques for reducing wake-up collisions and analyzing burst transmissions to lower the number of wake-up procedures (El Hoda Djidi *et al*., 2022)
- Implement 3D localization (i.e., estimation of node's altitude) under NLOS conditions (Niculescu *et al*., 2022)
- Add the support to large-scale networks (i.e., multi-hops via the MR) based on network area segmentation to limit waking-up flooding (Sampayo *et al*., 2021)
- Implement an adaptive wake-up estimation (e.g., using ML) for coping with high-traffic networks (Ali *et al*., 2020)
- When using mobile nodes, analyze the system's performance for scenarios with fewer charging stations than UAVs (Trotta *et al*., 2020)
- Investigate periodical queries in content-based wakeups (Shiraishi *et al*., 2023)
- Extend the solution to other radio transceivers, supporting multi-hop multi-sender networks with packet routing based on multiple decision policies
- (besides the one based on residual energy) (El Hoda Djidi *et al*., 2018)
- Design a hybrid solution for selecting which nodes to wake up and, possibly, maintain a backbone of nodes in duty cycle mode to facilitate the waking up process, including the possibility of waking up nodes in a specific path (Bannoura *et al*., 2015)

When employing passive WuRs, explore ways to use the harvested energy that is not used after the sensor node is woken up (e.g., charging the sensor's node battery) (Chen *et al*., 2015).

Table 5: Work's main open problems (future works)

Research field	Prominent future works
Management (Aranda *et al*., 2020; Ali *et al*., 2020)	• Data transmission prioritization (e.g., emergency handling) • Dead nodes' handling: out-of-operation nodes impact network coverage and connectivity, requiring their immediate replacement • Supporting switching between different channel access modes • Adaptive wake-up estimation (e.g., using ML) to cope with high-traffic networks
Scalability (Aouabed *et al*., 2022; Sampayo *et al*., 2021; Bannoura *et al*., 2015; Shiraishi *et al*., 2023)	• Explore multi-objective optimization methods for clustering of nodes • Large-scale networking (i.e., multi-hops via the main radio) based on network area segmentation to limit waking-up flooding • Explore a hybrid solution for selecting wake-up nodes and, possibly, maintain a backbone of nodes in duty cycle mode to facilitate the waking-up process including the possibility of waking up nodes in a specific path • Investigate scale properties of periodical queries in content-based wake-ups
Physical layer enhancements (El Hoda Djidi *et al*., 2022; Trotta *et al*., 2020)	• Research energy-efficient network coding techniques for reducing wake-up collisions • Handling of burst transmissions to lower the number of wake-up procedures • For the case of passive WuRs, explore ways to leverage the harvested energy not used after the sensor node is woken up (e.g., use it to charge the sensor's node battery)
Localization and mobility (Niculescu *et al*., 2022)	• 3D localization (i.e., estimation of node's altitude) under NLOS conditions • For scenarios with mobile nodes (e.g., UAVs), analyze the system's performance with fewer charging stations than UAVs

Discussion and Conclusion

To guarantee coverage of the area of interest and device connectivity, primarily it is paramount to understand the application's target phenomenon; next, there are the hardware and communication technologies involved, the characteristics of the physical environment (e.g., the topography of the network deployment environment), the accessibility to the devices for maintenance (including potential replacements of batteries and components), the network autonomy (none, partial, or total) and the support for mobile devices (ground, submerged, air, hybrid). At the same time, it is also strictly vital to balance all these aspects with the total system cost and the application's level of criticality.

In WSNs, likewise in many other battery-powered systems, keeping an active node idle represents a waste of energy, directly affecting the network's average lifetime. Devices in a WSN can, following a predefined schedule or one planned according to some learning process (e.g., using ML), define when and for how long to remain active. The primary motivation is extending the network's life without compromising the application's functioning. During periods of activity (duty cycles), the communication process between devices initiates, which can occur deterministically (free from collisions) or probabilistically (with contention and the possibility of collisions). On the other hand, an utterly asynchronous solution is always an option, activating devices on demand.

Efficient energy management involves minimizing active idle time without compromising the application's quality of service. Hence, activating a device on demand (i.e., asynchronously) represents one possibility to achieve this goal; nonetheless, the solution involves defining decision criteria regarding when and which device to wake up. Using WuRs represents a viable and promising path to implementing such an approach. Meanwhile, as they become an integral part of the application, enhancements to the radio itself take place, enabling additional performance improvements.

The insertion of WuRs into WSNs was the main focus of this literature review. WuRs are fundamental in asynchronous communication between network devices in all analyzed works: Protocol proposals, pure analytical analyses, energy models, and prototypes. In general, the following conclusions are prominent:

- When the WuR is a sensor device's primary on-demand activation entry, one expects it to spend the minimum possible energy because it must always be on and listening (assuming active radios). Thus, the strict low-power mode operation translates into a much lower communication range than the main radio. In a few words, it is possible to wake the target node only at shorter distances (in the case of passive radios, such achievable distances are invariably shorter). Even when the MR plays both roles (in-band mode), it must operate in the lowest possible power mode. Thus, we face the first tradeoff when deciding to go with WuRs
- Taking the WuR's central problem as the handling of the wake-up signal, it can be directed to a specific device (based on an addressing scheme), a group of devices (the radio interface could have multiple addresses), or, in the worst case, all devices (i.e., broadcast). Process optimization occurs when waking up only the devices strictly necessary for the task. Works show that it is possible to integrate an additional criterion for triggering the primary device's activation process into the identification

procedure. In this case, one can decide, for example, to request activation only if the target device has valid data to transmit (e.g., by specifying data timeliness and range limits)

- On their gradual adoption in WSNs, WuRs got proposals for new features such as (a) adjustments to the channel handling (e.g., channel bandwidth customizations, improved coding techniques), letting enhanced operation under constrained interference levels, including reaching more extensive radio ranges; (b) support for radios with multiple addresses (opening way for extensive selective waking-up procedures); and (c) improved energy-efficient microcontrollers dedicated to WuRs allows to refine the waking-up criteria (i.e., actions in addition to the usual address handling) and, eventually, include some initial payload (very short) into the waking-up signal itself
- Both event-driven solutions (i.e., when the source of information initiates the waking process) and an activation starting at the sink (i.e., polling) usually require waking up multiple intermediate devices during the relaying process until reaching the target. This results from the shorter transmission/reception range when using WuRs. However, data communication generally occurs in a single hop (i.e., directly) when the source and destination are ready. Therefore, the star topology is central to most of the solutions analyzed in this review
- Some solutions optimize forwarding the wake-up signal, employing on-demand decision criteria (e.g., remaining energy) or some infrastructure reproducing a backbone of nodes responsible for forwarding the wake-up signal
- When routing is available at the main radio level (i.e., real multi-hop network), works explore hierarchical clustering and path optimization regarding energy savings. However, it is worth emphasizing again that most works focus on single-hop data communication to the sink (i.e., star topology)
- When the total deployment cost of equipping all nodes with WuRs is prohibitive, they might still have a performance impact when employed partially. For example, when backup nodes are needed to assume some extra network load or handle urgent data temporarily, we can activate them on demand to help accomplish the assignment
- Synchronous and asynchronous communication can coexist, and WuRs are one viable way to manage transitions between them or even provide solutions for both modes simultaneously

Due to the inherent tradeoffs associated with WuRs' features, the reviewed works show that the power-saving benefits are felt primarily in WSNs with low data rate profiles. Nevertheless, that does not rule out WuRs as the main asynchronous communication element (full-time or as a backup) in critical scenarios. When critical events are relatively intermittent and do not result in communicating large datasets, resorting to asynchronous communication pays off. Otherwise, it is always possible to plan for a hybrid solution.

Many security concerns have yet to receive due attention, with some works presenting the subject as a priority for future works. Nevertheless, security will likely receive proper attention, mainly because all the fundamentals extensively described throughout the reviewed works provide practical communication solutions. To give the context for a potential security threat, let us consider the possibility of a Denial of Service (DoS) attack when employing broadcast-based waking-up procedures. An attacker could quickly deplete a node's battery by consistently sending waking-up commands. Such an attack is also called denial of sleep (Shakhov and Koo, 2018).

Our last observation concerns WuR technology specifically. The main results indicate scenarios where significant gains are possible when employing WuRs, not only in energy savings but also in enabling new coordination strategies among sensor nodes. In this context, there is much to research regarding device diversity, such as exploring the coexistence of distinct WuRs technologies (e.g., active and passive) in a single solution.

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Author's Contributions

Marco Aurélio Spohn: Designed the research plan and supervised its execution. Most of the writing.

Caetano Mazzoni Ranieri: Contributions to drafting the article.

Agnelo Rocha da Silva: Contributions to drafting the article.

Jó Ueyama: Contributions to drafting the article.

Ethics

This article is original and contains unpublished material. The authors confirm that they have read and approved this document and that no ethical issues are involved.

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