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Relatório de Pesquisa

Afastamento Pós-doutorado

Período: março 2024 a fevereiro 2025

Pesquisador Visitante:	Dr. Marco Aurélio Spohn Professor Titular – UFFS
Supervisor:	Dr. Jó Ueyama Professor Titular – ICMC/USP

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Resumo

O presente relatório descreve as principais realizações do Pesquisador Dr. Marco Aurélio Spohn (Professor Titular, UFFS) durante sua visita (pós-doutoramento) no ICMC/USP (São Carlos, SP) com atividades realizadas no período de 01 de março de 2024 a 28 de fevereiro de 2025.

Conteúdo

Capítulo 1

Introdução

Este relatório descreve as principais atividades e resultados obtidos durante a visita do Pesquisador Dr. Marco Aurélio Spohn (Professor Titular, UFFS) no período de março de 2024 a fevereiro de 2025 no ICMC/USP (São Carlos, SP).

As atividades desenvolvidas estão relacionadas ao projeto *MonDesa – Sistema Autônomo para Monitoramento de Desastres com Tecnologias de Despertar por Radiofrequência*. O mesmo contempla um planejamento de pesquisa por um período total de dois anos com a participação de uma equipe composta por quatro pesquisadores principais. Além destes, contempla a participação de uma equipe de alunos de graduação e pós-graduação vinculados ao ICMC/USP.

Para o primeiro ano da pesquisa, planejou-se realizar uma revisão sistemática da literatura relacionada à aplicação de tecnologias de despertar por radiofrequência (i.e., *Wake-up Radios*) em redes de sensores sem fio, bem como a proposta de novas métricas de qualidade em telemetria para aplicações de monitoramento de desastres. No entanto, devido a uma redefinição de prioridades no projeto, decidiu-se por, após elaboração da revisão sistemática, pesquisar alternativas de comunicação mais adequadas aos cenários de monitoramento e prevenção de desastres.

A adoção de WuRs permite estender o tempo de vida de uma rede de sensores com dispositivos alimentados por baterias não recarregáveis. Portanto, considerando-se que aplicações de monitoramento de desastres (sobretudo deslizamentos de terra) operam em locais e condições inóspitas, dificultando o acesso para manutenção e substituição de componentes (incluindo, nesse caso, baterias), torna-se imprescindível adotar soluções econômicas em consumo de energia. Neste contexto, a pesquisa possibilitou identificar que a tecnologia de WuRs tem um potencial promissor em aplicações relacionadas ao tema principal desse projeto.

Apesar do tempo reduzido de pesquisa, conseguiu-se produzir uma revisão sistemática a contento. Os resultados servem como uma base sólida para o planejamento e execução das etapas seguintes do projeto. Além disso, permite o planejamento de projetos futuros correlatos, contemplando a continuidade da participação do Pesquisador Visitante desde sua Instituição de origem (i.e., UFFS).

Além desse resultado, destaca-se a proposta de uma arquitetura de comunicação multi-protocolo inovadora no contexto de aplicações críticas como aquelas relacionadas ao monitoramento de encostas com fins de detecção de deslizamentos e prevenção de desastres. A arquitetura explora a diversidade de dispositivos de comunicação, empregando WuRs como peças fundamentais na orquestração dos elementos comunicantes na arquitetura. Já em continuidade nessa linha, tem-se uma equipe de alunos de graduação trabalhando em um primeiro protótipo baseado na arquitetura proposta.

O restante desse relatório está organizado da seguinte forma. No Capítulo 2 descreve-se as principais atividades realizadas. No Capítulo 3 apresentamos as conclusões, destacando-se que os principais elementos textuais produzidos encontram-se nos Apêndices A e B.

Capítulo 2

Atividades desenvolvidas

O projeto de pesquisa de referência (i.e., *MonDesa*) tem como propósito avançar a pesquisa na área de monitoramente e prevenção de desastres naturais, com atenção especial a deslizamentos de terra. Quando os equipamentos de monitoramente são alimentados por baterias não recarregáveis, torna-se crítico realizar o gerenciamento de energia da forma mais eficiente possível, prolongando-se a vida útil do sistema de monitoramente.

Considerando-se que o projeto prevê atividades para um período de dois anos e a participação de pesquisadores de múltiplas Instituições, destaca-se que esse relatório corresponde ao período de doze meses correspondentes à visita do Prof. Marco Aurélio Spohn no ICMC/USP. Portanto, neste capítulo descrevemos as principais atividades realizadas durante o período da visita. Resumidamente, as atividades desenvolvidas foram as seguintes:

- Elaboração de uma revisão sistemática da literatura referente a aplicação de *Wake-up Radios* em Redes de Sensores Sem Fio: o Apêndice A inclui uma versão completa da revisão sistemática.

- Proposta de uma arquitetura de comunicação multi-protocolo aplicada em sistemas de monitoramento e prevenção de deslizamentos de terra: o Apêndice B apresenta detalhamento da arquitetura proposta.

- Reuniões periódicas com o Pesquisador Responsável e membros da equipe (incluindo um membro externo).

- Auxílio na supervisão de alunos da graduação e pós-graduação.

- Visita técnica ao Centro de Monitoramento e Alertas de Desastres (CEMADEN) em São José dos Campos, SP (convite para a visita é apresentado no Apêndice C).

- Tratativas de cooperação com o CEMADEN para realização de pesquisas relacionadas à prevenção de desastres relacionados a deslizamentos de terra: em setembro de 2024 realizamos uma primeira reunião com representante do CEMADEN para tratativas de parcerias para projetos a serem submetidos a agências de fomento.

Assim como já enfatizado no capítulo anterior, avaliou-se como mais prudente dar prioridade à melhor compreensão dos potenciais da aplicação da tecnologia de WuR no monitoramento e prevenção de desastres relacionados a deslizamento de terra. Portanto, deu-se prioridade à revisão sistemática da literatura relacionada a esse tema.

Além disso, com fins de propiciar condições à continuidade do projeto de forma mais fluida e facilitar a participação futura do pesquisador visitante desde sua Instituição sede, investiu-se na proposta de uma arquitetura de comunicação orientada à diversidade de tecnologias e protocolos. A arquitetura apresenta qualidades e particularidades que permitem seu amplo emprego em aplicações de monitoramento remoto em locais inóspitos e uma expectativa de operação desassistida por períodos longos e compatíveis aos requisitos das aplicações de prevenção de desastres. Objetivando apresentar um primeiro estudo de caso, já há uma equipe de alunos de graduação (no ICMC) trabalhando em uma primeira implementação de um protótipo de uma plataforma de sensoriamento de umidade do solo contemplando a arquitetura de comunicação proposta.

Capítulo 3

Considerações finais

A visita do Prof. Marco Aurélio Spohn ao ICMC/USP foi muito frutífera, rendendo a produção de um artigo completo de revisão sistemática, a proposta de uma arquitetura de comunicação multi-protocolos (explorando propriedades da diversidade na comunicação), reuniões formais e informais com membros da equipe (pesquisador responsável e orientandos da graduação e pós-graduação) e uma visita ao CEMADEN.

Esses resultados indicam possibilidades promissoras na continuidade da parceria entre o Prof. Marco Aurélio Spohn e o Prof. Jó Ueyama. Tem-se, de imediato, o projeto de implementação de um primeiro protótipo da arquitetura de comunicação multi-protocolos que, no presente momento, conta com a participação de dois alunos da graduação com dedicação ao projeto. Espera-se, de igual forma, colaboração futura na orientação conjunta de alunos da pós-graduação.

Da visita ao CEMADEN em maio, resultou uma parceria que prevê cooperação entre as partes em projetos futuros. Dentre estes, espera-se avaliar a adaptação de uma plataforma de sensoriamento de umidade de solo, com tecnologia nacional e de custo reduzido, em aplicações de monitoramento de regiões propensas a deslizamentos de terra. O processo envolve estender a plataforma tanto em requisitos de *hardware* como de *software*, inclusive contemplando a arquitetura de comunicação multi-protocolo.

Em termos de publicações, espera-se que uma versão adaptada da revisão sistemática seja publicada em um periódico relacionado à área e reconhecido no sistema de avaliação Qualis. Os projetos que prosseguem tem potencial de resultar em publicações científicas e patentes.

Apêndice A

Versão completa da revisão sistemática

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 work 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

1. 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. WiFi and Mobile/Cellular communication are examples of the former. In the latter scenario, the primary representatives are the Mobile ad hoc Networks (MANETs) [1, 2, 3, 4, 5]. Meanwhile, as a hybrid approach, we have the Wireless Sensor Networks (WSNs) [6, 7, 8]. In many applications, WSNs enable the Internet of Things (IoT) [9].

Analytical studies [10] 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 subchannels. On the other hand, when node mobility is present, it creates a more diverse environment, increasing the network capacity [11, 12].

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 [5]. 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) [13]; 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 trade-off 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) [14]. Such radio is usually the single active component on a sleeping node: once a valid wake-up signal is received, a procedure gives rise to starting the remaining node's components.

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 [15].

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 1 mW [14, 16, 17]. 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 [18]. 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 [14]. 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 work 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. Table 1 shows the essential acronyms and abbreviations and their complete

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
EDT	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

forms used throughout the paper. The remainder of this work is structured as follows. Section 2 presents the basics of WSNs, and Section 3 delivers the basics of WuRs, including a taxonomy for WuR devices. Section 4 outlines our research methodology. Section 5 deals with the literature review and our research results, and Section 6 presents our findings.

2. 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

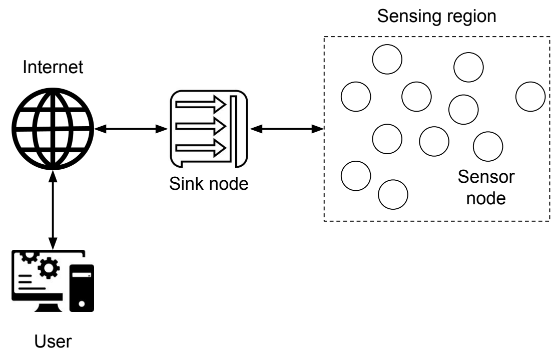


Figure 1: Typical elements in a Wireless Sensor Network.

of the primary topics inherent to the works in our systematic review.

A WSN (Figure 1) comprises devices (sensor nodes) with sensing and actuation capabilities connected through wireless communication [6, 7]. 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 [8].

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. [19] 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. [20] 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. [21] survey 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.

Jeng et al. [22] propose a path-planning scheme for wireless sensor networks with mobile sinks. Such 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, which 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. [23] 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 [24] 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.

3. Wake-up Radios

Following a similar path to that taken for WSNs, this section 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, a synopsis of the various WuR approaches currently available in the literature. To help better apprehend these and other related elements, we present our taxonomy for WuR devices.

3.1. 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. [25] 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 [26] investigated the tradeoffs between WuR and regular WSNs under different duty cycles. When nodes remain sleeping most of the time, 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 [14].

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 for the node to be ready for activation, sensing, and data communication.
2. When employing a regular WSN radio as part of the WuR receiver, the sleeping energy is significantly reduced by applying a duty cycle to the radio. Therefore, the maximum period when the radio can be regularly powered off or maintained in an inactive state also imposes an 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.

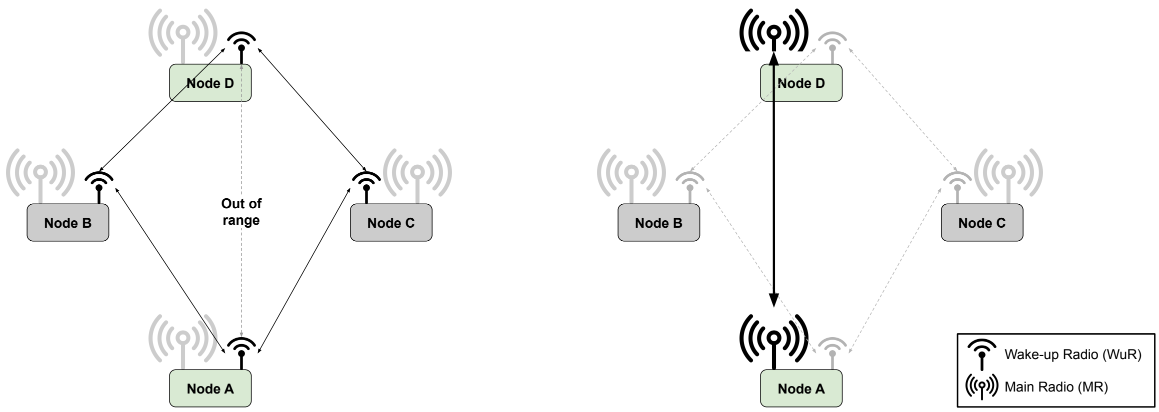
The usual situation is maintaining a shorter radio range when operating with the WuR (Figure 2), which results from a lower power transmission compared to the main radio (MR). In this architecture, the wake-up process occurs progressively as each node wakes its nearby neighbors, eventually reaching the 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 [1]) showing similar transmission and reception consumption [27]. Hence, shorter WuR ranges can potentially impact energy savings on both endpoints (i.e., transmitter and receiver).

3.2. *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 Silva et al.[14] 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 Section 1, there are roughly two variants of WuRs: active and passive (see Figure 3). In the active mode, the WuR-Rx device remains continuously listening while the other device's components stay inactive (i.e., completely turned off or in a deep sleep state). 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

[1] For Texas Instruments™ CC2652R [27], reception (RX) current is 6.9 mA, and transmission (TX) current is 7.0 mA at 0 dBm.



(a) Radio range during WuR-Tx.

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

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

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) [28]. 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. [29] 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.

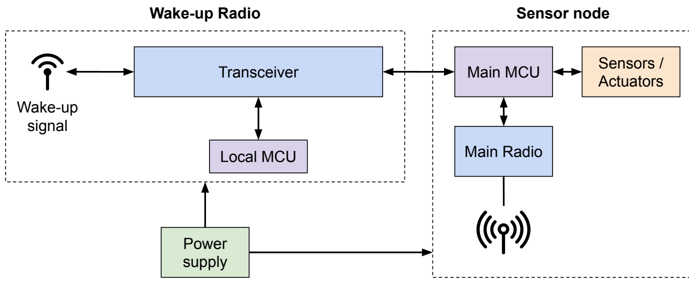
Silva et al. [14] propose address matching in the analog domain with no symbol decoding: to match, the wake-up call continuous wave frequency must correspond to the one pre-configured at the receiving WuR. In addition, the receivers have filters configured with non-traditional bandwidth, resulting in 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.

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

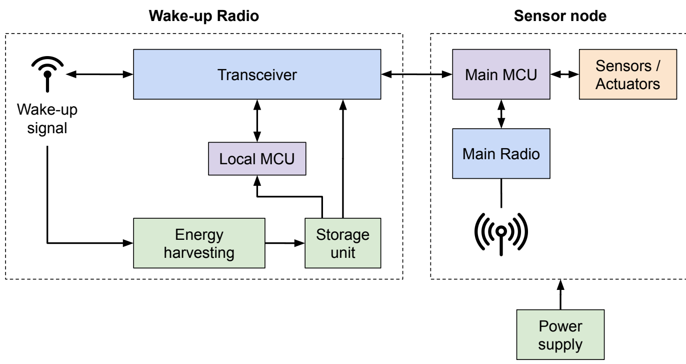
4. Methodology

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?



(a) Active Wake-up Radio.



(b) Passive Wake-up Radio.

Figure 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).

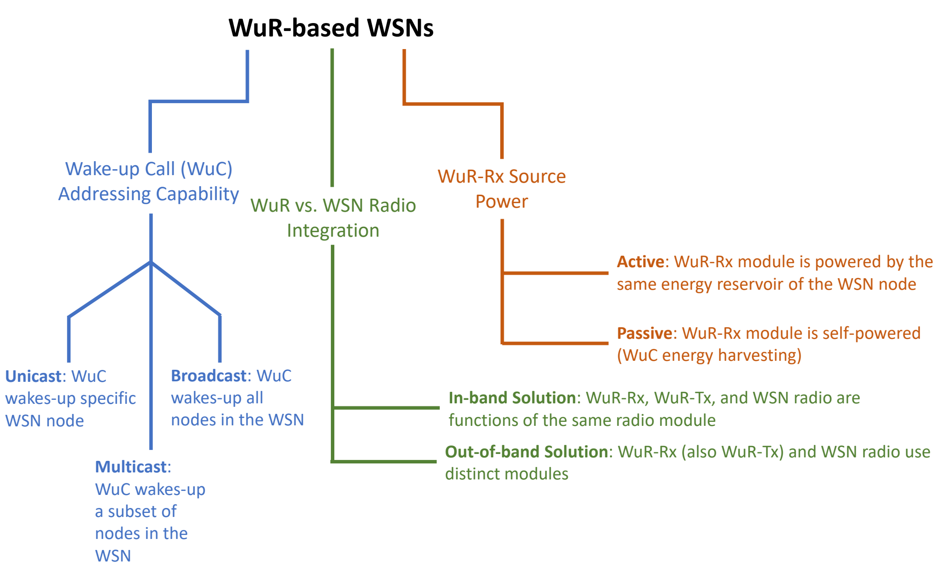


Figure 4: A taxonomy for WuRs applied to WSNs.

4.1. 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 take a closer look at these criteria.

The inclusion criteria are papers published in English within the last ten years (i.e., 2014 to 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 checking each work manually. We want to focus only on works that strictly count on WuRs in the research problem addressed in WSNs.

4.2. 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 chosen to consider only works that follow the scientific method as their primary foundation and are published by globally recognized publishers such as IEEE, ACM, ScienceDirect, Springer, and MDPI.

4.3. 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"].

5. 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.

The literature review and the research results are blended into this section to make the process direct and to the point. Nonetheless, Appendix A presents a summary of each reviewed paper[2].

[2]The appendix includes a summary of each reviewed paper, highlighting the following aspects of the individual works: main contribution, WuR roles, validation aspects, limitations, and future works.

5.1. ***RQ1:*** *What are the works' research topics and their main results?*

The works' primary research topics relate to:

- Physical and MAC [14, 30, 31];
- MAC [32, 33, 34, 35, 36, 37, 38, 39];
- MAC and routing [40, 41, 42, 43, 44, 45, 46, 47, 48, 49];
- MAC and localization [50];
- Content based polling [51];
- Broadcasting [52, 53];
- Cross-layer communication [54, 55];
- Prototyping[56];
- Energy modeling [57];
- A case advocating for WuRs in WSNs [58].

Most works focus on improving the network lifetime while balancing energy consumption and other performance metrics (e.g., connectivity reliability, latency, and coverage requirements).

5.1.1. ***Physical and MAC***

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

Silva et al. [14] 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.

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

Chen et al.[30] propose improvements to extend the activation range for passive WuRs. In particular, the design introduces two energy efficiency features: an improved energy harvester circuit and an enhanced MCU triggering mechanism for handling WuCs. A real testbed is presented and evaluated. Results include extensive simulations (in Matlab), comparing the proposed solution with other passive and active radios, and a duty cycle protocol. The results show that the proposed solution outperforms the others in network lifetime, latency, and packet delivery ratio.

Petrioli et al.[31] design 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 convergecasting (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.[33] 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 there is no address matching, 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 for 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.[37] present a WuR prototype based on LoRa's long-range technology. The solution includes a power-efficient microcontroller for supporting selective wake-ups based on the 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.

5.1.2. ***MAC***

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

Ali et al.[32] design an asynchronous duty-cycle MAC protocol, with sink nodes remaining 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.

Aoudia et al.[34] 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.

Dijdi et al.[35] 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 microbenchmarks show a lifetime gain of up to 1.7 when using two relayers.

Ghose et al.[36] propose three MAC protocols suited for different traffic patterns, assuming event-driven WSNs with star topologies. The solutions explore clear channel assessment (CCA), backoff 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 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.[38] 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.[39] design 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.

5.1.3. ***MAC and routing***

Liu et al.[49] 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.[48] 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). Power consumption reduces due to on-demand WuR node activation. Simulations with Matlab show the clustering solution outperforming two representative protocols, improving network lifetime and packet delivery (no results regarding latency).

Huang et al.[41] 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.[42] 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 et al.[43] 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 validation uses a Markov chain model. The results show that the protocol performed superiorly compared to other protocols.

Trotta et al.[44] 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 OM-

NeT++ simulator. Results show a lifetime enhancement of up to 30% compared to a traditional duty cycle solution.

Pegatoquet et al.[45] 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.[46] 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.[47] 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)[3] [59] limitations, such as 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.

[3] LoRa Wide Area Network (LoRaWAN) defines LoRa's communication protocol and system architecture [59].

5.1.4. ***MAC and localization***

Niculescu et al.[50] 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 waypoint 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 5m and 20m.

5.1.5. ***Content based polling***

Shiraishi et al.[51] proposed a solution for content-based wake-up (CoWu): sensor readings are helpful only if they comply with the requested criteria (range interval) and they can get to the sink node before the deadline (accuracy). Numerical results show enhanced accuracy and better energy efficiency when compared to a round-robin approach.

5.1.6. ***Broadcasting***

Bannoura et al.[52] 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.[53] 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.

5.1.7. ***Cross-layer***

Aranda et al.[54] 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.[55] 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.

5.1.8. ***Prototyping***

Cabarcas et al.[56] present an open platform, based on open software and COTS hardware components, for prototyping WSN applications with WuR capabilities. A module unit allows on-board precise power monitoring for the WuR module and the sensor node. Based on a real network with linear topology, they show how one can measure power consumption and latency.

5.1.9. ***Energy modeling***

Aranda et al.[57] present an energy model for estimating energy savings on WSNs based on WuRs. The model captures the impact of employing specific WuRs capabilities (e.g., addressing), assuming in-band WuRs and multi-hop networks. Validation is based on analytical results for various network scenarios, showing that WuRs can significantly extend the network lifetime in multi-hop networks with short event periods compared to low-duty cycle approaches.

5.1.10. ***A case advocating for WuRs***

Based on actual hardware specifications and a representative network simulator (i.e., OMNET++) with the proper features for seamless simulation of WuRs, Oller et al.[58] compare the most representative duty cycle protocols with their protocol based on WuRs. Several realistic WSN scenarios are extensively evaluated through the proposed simulation environment, showing that WuRs deliver a genuine performance leap compared to standard duty cycle approaches.

5.2. ***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 the wake-up signal is received (broadcast mode).
- Waking up selectively:
  - Based on some addressing mechanisms, including allowing the device to have multiple addresses, 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, for example, range limits; that is, wake a node up only if its retained data is not outdated and it 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 (convergecast). 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.

5.3. ***RQ3:*** *What are the works' main limitations?*

The research's findings and conclusions, which are deeply rooted in their underlying premises, are a testament to the complexity of our analysis. It is crucial to underscore that our understanding builds upon these intricate assumptions and their far-reaching implications.

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 using WuRs to enhance power management, particularly in low-data rate scenarios, which is a significant finding that emphasizes WuRs' potential benefits. However, it is essential to note that energy consumption can increase significantly in higher data rate scenarios due to frequent waking-ups. 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 overlooking the basic layers: physical [48], or physical and link [41];
- Simplistic channel modeling: error-free transmissions [51][43][57], an infinite retransmission limit [43], or interference effects ignored [33];
- Routing overhead disregarded (routing tables computed offline) [40];
- Assuming only in-band WuRs with the same radio range as the MR [57].

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

- No wake-up addressing mechanism (i.e., broadcast mode), being more prone to false positives [49] [54] [30] [53];
- Node localization restricted to 2D assuming line of sight [50];
- Information regarding sensor node deployment/location as a prerequisite [44];
- Use of passive WuRs, limiting the distance between neighboring nodes [44];
- Restricted data traffic settings (e.g., uniform packet rate and size) [32];
- Support only WSNs with a single sink [48][45][34];
- Strictly limited evaluation scenarios: routing evaluation with just two relayers [35], clustering evaluation with a few nodes in a single cluster [47], and the validation relying on a single node [37];
- Incorporation of new WuR technologies might be a limiting factor with prototyping platforms [56].

5.4. ***RQ4:*** *What are the open problems?*

Several works [54][56][43][44][33][45][57][36][37] 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.

Among the most prominent future works, there are the following:

- Explore management options for prioritizing data transmissions during emergencies, support handling dead nodes, and allow dual switching between channel access modes [54].
- Explore multi-objective optimization methods for clustering of nodes [48].

- Research energy-efficient network coding techniques for reducing wake-up collisions and analyzing burst transmissions to lower the number of wake-up procedures [40].

- Implement 3D localization (i.e., estimation of node's altitude) under NLOS conditions [50].

- Add the support to large-scale networks (i.e., multi-hops via the MR) based on network area segmentation to limit waking-up flooding [42].

- Implement an adaptive wake-up estimation (e.g., using ML) for coping with high-traffic networks [32].

- When using mobile nodes, analyze the system's performance for scenarios with fewer charging stations than UAVs [44].

- Investigate periodical queries in content-based wake-ups [51].

- 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) [35].

- 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 [52].

- When employing 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) [30].

6. Discussions and Conclusions

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 that reproduces 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 total deployment cost is prohibitive for equipping all nodes with WuRs, they might still have a performance impact when employed partially. When backup nodes are needed, for example, to assume some extra network load temporarily or to handle urgent data, we can activate the nodes 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.

In general, 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, it pays off to resort to asynchronous communication. 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 [60].

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.

Acknowledgement

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Appendix A. Reviewed articles' summaries

As explained previously, we opted for a concise yet complete structure for the main body of our systematic literature review. To deliver quick access, this appendix includes a summary of each reviewed article, highlighting the following aspects of the individual works: paper title and citation, main contribution, WuR roles, validation aspects, limitations, and future works.

DDSR: A delay differentiated services routing scheme to reduce deployment costs for the Internet of Things [49]

This work proposes a routing solution for differentiated services (i.e., regular and urgent data) with low latency and efficient energy consumption. To reduce network cost deployment, only some nodes are equipped with WuRs. Their activation happens only when a regular node (i.e., without WuR) cannot handle the transmission. The solution guarantees a minimum number of nodes equipped with WuR while ensuring the routing of urgent data.

WuR roles. Contribute to supporting the differentiated service by handling part of the network routing load.

Validation. Validation is only theoretical (analytical). Results show that the protocol can handle regular and urgent data, outperforming other protocols regarding delay, network lifetime, and deployment costs.

Limitations. Validation does not consider any essential stack layers.

Future works. Address security when using both regular nodes and nodes with WuRs (e.g., explore ML to optimize the data routing path).

Query Timing Analysis for Content-Based Wake-Up Realizing Informative IoT Data Collection[51]

This work presents a solution for content-based wake-up (CoWu): sensor readings are valid only if they comply with the requested criteria (range interval) and can be delivered to the sink before the deadline (accuracy).

WuR roles. WuR awakes the node only if local data fits in sink request parameters. Instead of regular addressing, WuC length relates to the requested range limits.

Validation. Numerical results show enhanced accuracy and better energy efficiency than a round-robin approach.

Limitations. Analysis assumes a simplistic channel model, error-free ACK transmissions, and all nodes within direct communication range.

Future works. Investigate periodical queries. Comparison using a more realistic channel model.

A Wake-up Radio-Based Energy-Efficient Multi-Hop Clustering Protocol for WSNs[48]

This work proposes a multi-hop (WuR range) clustering solution in single-hop (MR range) networks. Multi-hop path selection is based on nodes' residual energy and distance to cluster heads (CHs). On-demand WuR node activation reduces power consumption.

WuR roles. Multi-hop communication relies on WuRs for on-demand node activation in the routing path.

Validation. Simulations with Matlab show the clustering solution outperforming two representative protocols, improving network lifetime and packet delivery (no results regarding latency).

Limitations. The protocol assumes a one-hop (MR range) network with only one sink. Validation is analytical without full-stack modeling (e.g., a physical model is absent).

Future works. Extend the model with multi-objective optimization methods aiming for better performance results.

The revenge of asynchronous protocols: Wake-up Radio-based Multi-hop Multi-channel MAC protocol for WSN[40]

The work presents an out-of-band asynchronous MAC protocol for multi-hop WSNs. It assumes offline (pre-computed) paths between sensor nodes and the sink are available. The sink remains sleeping until the source sensor wakes it up.

WuR roles. All nodes in the path between the source and the sink are activated through WuRs.

Validation. Simulation results based on COOJA show the protocol outperforming three Time Synchronized Channel Hopping (TSCH) protocols regarding energy efficiency and latency, assuming low traffic scenarios. However, their solution presents slightly lower reliability.

Limitations. The work does not consider the routing protocol overhead (i.e., they assume routing tables are computed offline).

Future works. Reduce wake-up collisions using energy-efficient network coding techniques. Add support to burst transmissions to reduce wake-up procedures.

Fly, Wake-up, Find: UAV-based Energy-efficient Localization for Distributed Sensor Nodes[50]

The work introduces a solution for the 2D localization 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. Data transmission starts once the node is located.

WuR roles. WuRs are required to wake the target nodes asynchronously.

Validation. Validation based on synthetic data and with an actual flying drone. The results show sub-meter precision and a node's energy consumption 800 times smaller than realistic duty-cycle approaches. UAV energy consumption is not analyzed. Reasonable precision measures are possible when UAV height is between 5m and 20m.

Limitations. There is no energy-efficiency analysis for the UAV. The analysis is restricted to 2D localization assuming Line of Sight. However, preliminary results indicate that it is possible to adapt their solution to a 3D scenario with NLOS.

Future works. Implement 3D localization (i.e., estimate node's altitude). Extend the solution to work in NLOS conditions.

A parallel joint optimized relay selection protocol for wake-up radio enabled WSNs[41]

This work introduces 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.

WuR roles. Use WuRs to activate nodes towards the sink (convergecast).

Validation. Theoretical analysis and simulation-based experiments via Matlab compare the relaying approach to a basic tree forwarding scheme. Results point to promising performance improvements.

Limitations. The analysis and simulations do not consider all the essential stack layers.

Future works. Not mentioned.

REFLOOD: Reactive routing protocol for wake-up radio in IoT[42]

This work proposes 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 using the MR. The waking-up procedure also includes a load-balancing mechanism to leverage the multiple paths between the source and destination.

WuR roles. The waking-up procedure between source and destination is based on WuRs.

Validation. Extensive simulation results, based on the COOJA simulator, show that the routing solution allows up to 300% network lifetime improvements compared to duty cycle approaches.

Limitations. The solution is well suited for low data rate WSNs, mainly because it cannot handle concurrent WuC transmissions through the same set of nodes.

Future works. Add the support to large-scale networks (i.e., multi-hops on the MR). Segment the network into areas requiring a waking-up routing strategy to limit flooding.

A MAC Protocol for Energy Efficient Wireless Communication Leveraging Wake-Up Estimations on Sender Data[32]

This work introduces an asynchronous duty cycle MAC protocol. Sink nodes remain sleeping until they are awakened 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.

WuR roles. Essential for controlling the sink node activity (i.e., sender nodes awake the sink through its WuR).

Validation. Simulations based on the COOJA simulator. Results show good performance improvements for low data traffic.

Limitations. The solution performs well only for light data rate traffic. The simulations assumed an ideal-like environment with uniform packet size, rate, and low interference.

Future works. Implement an adaptive wake-up estimation (e.g., using ML) to cope with high-traffic networks.

A framework for multimodal wireless sensor networks[54]

This work presents a cross-layer framework for reliable and energy-efficient communication in multimodal WSNs. On-demand node activation reduces latency and increases the packet delivery ratio. The cross-layer interactions allow the proper tuning for regular and emergency events.

WuR roles. Essential for managing node activation for handling sensor nodes' data packet forwarding to the sink.

Validation. Based on an indoor proof-of-concept with four sensors and one sink. The proposed solution shows reduced latency and a better packet delivery ratio than a single-radio system.

Limitations. Broadcast-based wake-ups can be a significant problem for larger or denser networks (i.e., an increasing number of false positive wake-ups).

Future works. Include prioritizing packet transmissions during emergencies, dead node management, and dual switching between channel access modes. Design a practical evaluation platform for more extensive networks.

OpenWuR - An Open WSN Platform for WuR-based Application Prototyping[56]

This work proposes an open platform for prototyping WSN applications with WuR capabilities. A module unit allows on-board precise power monitoring for the WuR module and the sensor node. The platform is based on open software and COTS hardware components.

WuR roles. The WuR is the main element in the platform.

Validation. Based on a real network with linear topology, they show how to measure power consumption and latency.

Limitations. Platform extensibility to other WuR technologies could be problematic.

Future works . Evaluate the platform with more elaborate scenarios and protocols.

A Receiver Initiated Low Delay MAC Protocol for Wake-Up Radio Enabled Wireless Sensor Networks[43]

This work presents a receiver-initiated broadcast-based MAC protocol for WSNs. Clustering of nodes reduces contention. A theoretical basis for defining the optimal number of groups is also presented.

WuR roles. Essential for on-demand activation of nodes.

Validation. The protocol is evaluated using a Markov chain model. The results show that the solution performed superiorly to other protocols.

Limitations. The theoretical model is based on the assumptions of error-free channels and an infinite retransmission limit.

Future works. Extend the analysis for error-prone transmissions and a finite number of retransmissions.

BEE-DRONES: Ultra low-power monitoring systems based on unmanned aerial vehicles and wake-up radio ground sensors[44]

This work presents a WSN data-gathering approach based on multiple UAVs acting as mobile sinks, assuming they have charging stations. UAVs' paths are computed following a distributed or centralized approach. Quality of sensing data (Value of Sensing, VoS) is used as a metric to distribute the load evenly among ground sensors, which are awakened, using WuR, as the UAV hovers over them. The optimization framework considers the lifetime of ground sensors, UAV energy constraints, and VoS. The solution maximizes VoS when compared to greedy path-planning.

WuR roles. Passive WuRs solve the synchronization problem between UAVs and ground sensors.

Validation. Theoretical analysis and simulations based on OMNeT++ simulator. Results show a lifetime enhancement of up to 30% compared to a traditional duty cycle solution.

Limitations. Sensor node deployment must be known. Passive WuRs are only feasible for short distances between UAVs and ground sensors. UAVs are the most expensive components in the proposed framework.

Future works. The realization of a small-case testbed. The extension to a scenario with fewer charging stations than UAVs. The modeling of interference on aerial communications.

Enabling early sleeping and early data transmission in wake-up radio-enabled IoT networks[33]

This work introduces two improvements to WuCs' processing time and energy efficiency: early sleep (ES) and Early Data Transmission (EDT). ES reduces the processing time during overhearing: if there is no address matching, go back to sleep earlier. EDT includes 10 bits of payload data and the destination address, with and without ACKs. ES and EDT are mutually exclusive because EDT requires overhearing.

WuR roles. WuC handling is essential for any WuR.

Validation. Validation of the basic mechanisms using a real testbed. Performance results based on analytical and simulation (Matlab). Results show that the performance gains occur mainly for low data rate scenarios. Total overhearing energy consumption reduces primarily for 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 MR needs to wake up to send ACK.

Limitations. ES and EDT are mutually exclusive because EDT requires overhearing. Simulations do not take into account interference effects. With a heavy traffic load, the energy consumption due to overhearing becomes a dominant component for total device energy consumption, compromising the benefit brought by EDT compared to ES.

Future works. Incorporate the interference levels among concurrent transmissions under realistic channel conditions in the analytical model. Expand the testbed to a larger scale and perform more real-life experiments.

A Wake-Up Radio-Based MAC Protocol for Autonomous Wireless Sensor Networks[45]

This work introduces 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.

WuR roles. Essential for on-demand activation of nodes in the WuR path from BS to destination/polled node.

Validation. A prototype for indoor monitoring is used as a proof of concept (with sensors harvesting power from indoor light). OMNeT++ simulation results show the proposed protocol outperforms the state-of-the-art duty-cycle approaches regarding energy, latency, and collisions.

Limitations. The solution is suitable only for centralized single-hop topology.

Future works. Implement communication from sensors to the sink to report urgent events. Investigate the protocol performance in more extensive and denser networks.

Duty-Cycled, Sub-GHz Wake-up Radio with -95dBm Sensitivity and Addressing Capability for Environmental Monitoring Applications[14]

This work proposes an energy-efficient duty-cycle and WuR-based framework for sparse and star-based WSNs for outdoor monitoring. The solution enhances WuR communication reliability (no false positives) for more considerable distances under heavy RF interference for both NLOS and 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.

WuR roles. Enhancements to the WuR are the main focus for improving WSNs' performance.

Validation. The validation is based on 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.

Limitations. The solution is validated only for sparse one-hop WSNs. There is a tradeoff between distances and the delay in waking up. Address matching is restricted to the number of available frequency signatures and their pre-configuration of sensors.

Future works. Development of the theoretical model to support some aspects of the proposed WuR algorithm.

BLITZ: Low Latency and Energy-Efficient Communication for Event-Triggered Wireless Sensing Systems[46]

This work proposes 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.

WuR roles. Essential for the asynchronous communication mode.

Validation. A proof of concept based on an indoor testbed. The test case results show improvements in terms of latency and energy consumption.

Limitations. Due to the relaying process, there is a tradeoff between performance gains and the minimum number of sensor nodes.

Future works. Not presented.

Leveraging Energy Harvesting and Wake-Up Receivers for Long-Term Wireless Sensor Networks[34]

This work proposes a MAC protocol leveraging energy harvesting and WuRs. In the wake-up signal, the sink informs the sequence number of the next expected packet from the corresponding sensor node.

WuR roles. Asynchronous requests from the sink are relayed via WuRs.

Validation. Based on analytical analysis and an actual hardware implementation tested in real scenarios with star topologies. Results show that the protocol outperforms two state-of-the-art MAC protocols, achieving a 2.5 gain in throughput.

Limitations. The work assumes only star topologies.

Future works. Not presented.

An Energy Consumption Model for Multi-Modal Wireless Sensor Networks based on Wake-up Radio Receivers[57]

This work presents an energy model for estimating energy savings on WSNs based on WuRs. The model captures the impact of employing specific WuRs capabilities (e.g., addressing), assuming in-band WuRs and multi-hop networks.

WuR roles. The energy model is designed based on WuR in the WSN context.

Validation. Validation based on analytical results for various network scenarios. Compared to Low Duty Cycle approaches, results show that WuR can significantly extend the network lifetime in multi-hop networks with short event periods.

Limitations. Strong assumptions restrict analysis: only in-band WuRs, MR, and WuR with the same radio range, and no packet losses during communication.

Future works. Include packet losses in the model and extend the experiments to a real testbed.

Adaptive relaying for wireless sensor networks leveraging wake-up receiver[35]

This work introduces an energy-efficient MAC protocol leveraged on WuRs. It is assumed 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). An About to Send (ATS) message is sent before transmitting a data packet. If the source decides to send directly, it sends an ATS instructing the other nodes not to relay.

WuR roles. WuR is essential for activating nodes.

Validation. A prototype is presented as a proof of concept for the proposed protocol. Performance evaluation with analytical models and microbenchmarks shows a lifetime gain of up to 1.7 when using two relayers.

Limitations. The validation scenario has only two relayers.

Future works. Extend the solution to other Transceivers. Implement support to multi-hop multi- sender networks, including decision policies.

MAC Protocols for Wake-Up Radio: Principles, Modeling and Performance Analysis[36]

This work proposes three MAC protocols for different traffic patterns, assuming event-driven WSNs with star topologies. The solutions explore clear channel assessment (CCA), backoff plus CCA, and adaptive WuC transmissions.

WuR roles. WuRs are essential for the on-demand node activation.

Validation. An analytical framework based on an M/G/1/2 queue is used to evaluate the protocols' performance, and discrete-event simulations validate the analytical model's accuracy. Results show the protocols outperform a reference MAC protocol in energy consumption and WuC losses but perform worse in packet latency.

Limitations. The analysis assumes only star topologies.

Future works. Analyze the impact of error-prone channels on the protocol's performance. Investigate the possibility of wake-up signal generation based on pseudo-orthogonal sequences. Implement and analyze the protocols in a real testbed.

On-Demand LoRa: Asynchronous TDMA for Energy Efficient and Low Latency Communication in IoT[47]

This work proposes a solution that combines 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 LoRaWAN limitations, such as its inability to communicate on-demand with end devices.

WuR roles. WuRs are essential for the cluster head to wake up the end nodes.

Validation. An indoor testbed with 11 sensors is used to validate and test the architecture: 9 end nodes, 1 CH, and 1 sink. Preliminary results show that the solution is scalable and energy-efficient, and it can achieve 100% reliability. For the testbed, the system is estimated to have a lifetime of three years, assuming nodes are equipped with low-capacity batteries.

Limitations. The validation is based on a cluster with a few nodes.

Future works. Not presented.

Demo: Enabling Asynchronous Awakenings in Wireless Sensor Networks Towards Removing Duty-Cycle Barriers[37]

This work introduces a prototype of a WuR using the long-range technology LoRa. The solution includes a power-efficient microcontroller for supporting selective wake-ups based on the destination address decoding.

WuR roles. Essential for on-demand activation of nodes.

Validation. A testbed validates a single node, which consumes around 700 nA in the listening state and 1.8 uA during the active state.

Limitations. The work does not consider a real WSN scenario for device validation.

Future works. Validate the device in real WSNs' scenarios, varying the WuR range and the waking-up interval.

Has time come to switch from duty-cycled mac protocols to wake-up radio for wireless sensor networks?[58]

Based on actual hardware specifications and a representative network simulator (i.e., OMNET++) with the proper features for seamless simulation of WuRs, this work compares the most representative duty cycle protocols with the authors' protocol based on WuRs. Several realistic scenarios are extensively evaluated through the proposed simulation environment, showing that they have a point when saying that WuR provides a real performance leap compared to standard duty cycle approaches.

WuR roles. WuR is the primary analysis element in the WSN context.

Validation. The validation and their main contribution merge when providing the simulator dependencies and configurations for correctly simulating realistic scenarios with WuRs. The results corroborate their claim that WuR is a real improvement compared to duty cycle approaches in energy savings, higher PDR, lower latency, and more straightforward software implementations.

Limitations. An additional radio increases the cost of sensor nodes.

Future works. Not presented.

The wake up dominating set problem[52]

This work presents theoretical and practical results for the on-demand activation of a connected, energy-efficient dominant set, aiming to wake up a large set of all sensor nodes in a network via WuR. The proposed solution minimizes the number of wake-up signals transmitted to increase coverage and reduce energy consumption.

WuR roles. The connected dominating set is built around the WuR topology.

Validation. Different variants of the proposed algorithms are simulated in a custom simulator, showing that they 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.

Limitations. The proposed solutions assume that the whole network needs to be awakened.

Future works. To circumvent the limitations of the proposed protocol, 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. It also envisions the possibility of waking up nodes across a specific path.

A Cross-Layer Communication Protocol with Transmission Power Adjustment for Energy Saving in Multi-hop MhWSNs[55]

In this work, following a non-traditional interaction model between layers, the network layer informs 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.

WuR roles. Required for the on-demand activation of cluster nodes.

Validation. vThe solution is validated through simulations on NS2. Results show energy savings, network lifetime, packet delivery ratio, and end-to-end delay improvements.

Limitations. For the static solution, only the WuR range is listed in the simulation parameters (the MR power transmission is adjustable in the dynamic variant). Cross-layer solutions are usually more challenging to incorporate in real platforms.

Future works. Not presented.

REACH2-Mote: A Range-Extending Passive Wake-Up Wireless Sensor Node[30]

Assuming that passive WuRs have a shorter activation range compared to their active counterparts, this work introduces an extended range passive WuR into a new device (REACH2), leveraging on a high-efficiency, energy-harvesting module and a very low-power wake-up circuit. In particular, the design introduces two energy efficiency features: an improved energy harvester circuit and an enhanced MCU triggering mechanism for handling WuCs.

WuR roles. WuR is the main element for introducing improvements in the WSN node.

Validation. A real testbed is presented and evaluated. Extensive simulations (in Matlab) are presented, comparing the proposed solution with another passive radio solution, an active radio solution, and a duty cycle solution. The results show that the proposed solution outperforms the others in network lifetime, latency, and packet delivery ratio.

Limitations. Motes cannot handle ID-based wake-ups (they do not have a dedicated MCU); they can only perform broadcast wake-ups, being prone to false positives.

Future works. Handling of false positives. As the harvested energy is not used after the sensor node is woken up, this energy can be used to charge the sensor node, potentially increasing the sensor node's lifetime.

Zippy: On-Demand Network Flooding[53]

This work presents an energy-efficient protocol for on-demand flooding of rare events in multi-hop WSNs. Neighboring nodes are awakened asynchronously (via WuRs) to communicate synchronously later. They employ carrier frequency randomization to support multiple simultaneous transmissions with little or no interference, which could benefit dense scenarios.

WuR roles. Essential for waking the neighbors up during flooding.

Validation. The system is evaluated in a controlled laboratory setting and an indoor testbed.

Limitations. The solution is prone to frequent false positives, which can compromise the synchronization between neighbors. The hardware uses commercially available components, but its complete specification is not open. The software is not open either. It is a flooding protocol that is desirable only when all or almost all nodes must receive the rare event data.

Future works. Among the future works, they propose investigating the adoption of modulation schemes more robust against noise, mitigating the false positive wake-ups, tackling erroneous node synchronization, improving data rate and packet size limits, further analyzing the network scalability, and investigate the type and location of antennas to improve the system's performance.

Benefits of Wake-Up Radio in Energy-Efficient Multimodal Surveillance Wireless Sensor Network[38]

This work introduces a two-tier (multimodal) surveillance WSN framework with WuR as the primary tracking activation mechanism. Infrared sensors track user presence, activating the primary camera devices through WuR communication.

WuR roles. WuR is essential for the tracking activation mechanism.

Validation. Analytical analysis and simulations using Matlab. The proposed solution is shown to be more energy efficient and faster than duty cycle approaches (two orders of magnitude lower latency).

Limitations. There is a clear tradeoff between performance and cost when comparing the two-tier proposal with a single-tier (i.e., infrared sensors integrated into the cameras).

Future works. Not presented.

Ensuring Survivability of Resource-Intensive Sensor Networks Through Ultra-Low Power Overlays[39]

This work presents a design of an energy-efficient overlay surveillance WSN leveraging ultra-low power infrared sensor nodes and WuRs. Infrared presence detection triggers the activation, via WuRs, of power-intensive nodes (e.g., cameras).

WuR roles. WuR is essential in the on-demand activation of power-intensive nodes.

Validation. Validation through simulations and an actual deployment. Results show that the proposed solution extends the network lifetime compared to other approaches.

Limitations. The solution assumes a predetermined distribution for sensor nodes, which is reasonable considering the target application (surveillance).

Future works. Improve the monitoring accuracy by adopting camera activation mechanisms based on the target movement characteristics (e.g., speed, direction).

A Novel Wake-Up Receiver with Addressing Capability for Wireless Sensor Nodes[31]

This work presents the design of a wake-up receiver architecture combining frequency-domain and time-domain addressing space for selectively addressing nodes (i.e., nodes may have multiple IDs). The solution supports a wake-up-enabled harvesting-aware communication stack that supports interest dissemination (commands from the sink to the sensor nodes) and convergecasting (from all sensor nodes to the sink).

WuR roles. Essential for on-demand node activation.

Validation. 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.

Limitations. There is a need to evaluate the proposed solution in more realistic WSN scenarios.

Future works. Not presented.

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Apêndice B

Proposta de uma arquitetura de comunicação multi-protocolo

Arquitetura de comunicação multi-protocolo para sistemas de monitoramente e prevenção de deslizamentos de terra

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2024

Abstract

Sistemas de monitoramento e prevenção de deslizamentos de terra dependem de mecanismos eficientes de comunicação. Dispositivos sensores são responsáveis pela coleta de dados do fenômeno monitorado, enquanto sistemas auxiliares (locais ou remotos) são responsáveis pelo processamento e análise dos dados. Dependendo da gravidade do fenômeno observado (e.g., eminência de deslizamento), deve-se comunicar prontamente os agentes externos responsáveis pelo monitoramento. Neste contexto, propõe-se uma arquitetura de comunicação multi-protocolo que tem na diversidade de alternativas de tecnologias e protocolos o seu principal atrativo. Tendo-se à disposição alternativas de comunicação, pode-se empregar a que melhor atende os requisitos de qualidade relativos à criticidade dos eventos; inclusive, pode-se empregar múltiplas alternativas de comunicação simultaneamente. Este documento apresenta os principais elementos da arquitetura de comunicação proposta, incluindo a descrição de uma plataforma de prova de conceito, objeto para trabalhos futuros.

1 Introdução

Este documento representa um primeiro rascunho (*draft*) de uma proposta de arquitetura de comunicação multi-protocolo para sistemas de monitoramento e prevenção de deslizamentos de terra. A arquitetura explora a diversidade de comunicação, objetivando-se oferecer melhores condições e garantias de comunicação em sistemas críticos de monitoramento.

Anualmente há múltiplas ocorrências de desastres resultantes de deslizamentos de terra em várias regiões geográficas do planeta, ocasionando perdas de vidas e econômicas; quanto maior a concentração populacional próxima à região do desastre, maior o número de vítimas fatais. Sem adentrar em questões sócio-políticas relacionadas às ocupações das regiões mais propensas a ocorrências de deslizamentos de terra, focaremos nas questões técnicas de monitoramento e prevenção de regiões propensas a esse tipo de desastre.

Um sistema de monitoramento compreende (i) todos os equipamentos envolvidos nos processos de coleta de dados do fenômeno monitorado (e.g., índice pluviométrico, umidade do solo, movimento do solo), e (ii) dispositivos de comunicação. Estes últimos são o foco principal da arquitetura proposta, tendo-se em consideração que seriam irrelevantes as demais etapas do processo de monitoramento caso não se consiga chegar aos agentes externos a informação necessária à tomada de decisões na eventualidade de eventos críticos.

A arquitetura proposta contempla múltiplos protocolos/tecnologias de comunicação, oferecendo um nível de confiabilidade de serviço ajustável às necessidades de criticidade do fenômeno alvo de monitoramento. A aplicação responsável pelo monitoramento seleciona, de acordo com critérios bem definidos, qual mecanismo/protocolo de comunicação é empregado na comunicação com agentes externos (e.g., centro de monitoramento).

Além da diversidade de dispositivos/protocolos de comunicação, explora-se o desacoplamento físico entre o sistema principal de monitoramento e as unidades de comunicação. Ou seja, torna-se requisito que cada unidade de comunicação seja auto-contida: o dispositivo deve ser de dimensões reduzidas e conter todos os itens necessários à sua operação autônoma. Para tanto, cada unidade deve contemplar: Microcontrolador/CPU, memória primária e secundária, dispositivo de comunicação (específico de cada protocolo/tecnologia embarcado) e fonte de energia, possivelmente baterias não recarregáveis. Subentende-se que todos os componentes de cada unidade estejam alojados em uma caixa de proteção apropriada, de pequenas dimensões.

Em síntese, assume-se uma unidade principal (controladora) interfaceando com os equipamentos de sensoreamento. A controladora seleciona, de acordo com critérios flexíveis e específicos das aplicações, qual unidade de comunicação ficará encarregada da comunicação com agentes externos. Para economizar o máximo possível de energia destas unidades, elas são ativadas sob demanda (i.e., assincronamente). Para esta ativação, pode-se empregar *Wake up Radios* (WuRs), dispositivos de rádio que permanecem na escuta por uma solicitação de ativação, mantendo-se os demais componentes do sistema desligados ou em estado de repouso profundo [6, 1].

2 Arquitetura do sistema

Essa seção descreve a arquitetura do sistema, em termos de seus elementos de *hardware* e *software*. Inicialmente, destaca-se que duas modalidades organizacionais são alternativas a uma solução de arquitetura, a saber:

- Plana (*flat*): todas as unidades encontram-se no mesmo nível hierárquico (i.e., apresentam o mesmo potencial de capacidades). Nesta configuração não há um coordenador, podendo-se alternar papéis entre as unidades disponíveis, garantindo-se um nível de tolerância a falhas gerenciável.
- Hierárquica: por intermediação de um coordenador, supervisiona-se as unidades subordinadas (de comunicação). O coordenador apresenta re-

cursos e funcionalidades diferenciados como, por exemplo, a capacidade de comunicação com agentes externos, na eventualidade de não conseguir empregar alguma das unidades regulares, maior capacidade de processamento e armazenamento e uma fonte de energia renovável (e.g., baterias recarregáveis empregando placas solares).

A nossa abordagem segue a arquitetura hierárquica, pela sua simplicidade e por melhor atender a necessidade de se ter unidades de comunicação auto-contidas e desacopladas (fisicamente) da unidade de sensoreamento. A Figura 1 ilustra os principais elementos de uma estação de monitoramento em conformidade com a nossa arquitetura, destacando-se os seguintes:

- Uma fonte de energia renovável (e.g., placas solares para carregamento das baterias);
- Uma unidade controladora, interfaceando com todos os sensores e realizando o gerenciamento dos demais componentes. Coordena as unidades de comunicação com o mundo externo (i.e., agentes externos).
- Unidades de comunicação: cada unidade é auto-contida, podendo ser removida ou adicionada ao compartimento que aloja a unidade controladora sem nenhuma necessidade de conexão cabeada. A ativação das unidades dá-se por mecanismos sem-fio como, por exemplo, Wake up Radios. Na figura, ilustra-se como exemplo unidades com suporte a comunicação com as tecnologias/protocolos Rede Celular 5G, LoRaWAN [4] e WiFi Long Range.

Propriedades do sistema:

1. *Health-check* e *self-healing*: por exemplo, empregando recursos de *watchdogs*, realizar verificações periódicas e, caso o sistema entre em um estado inconsistente de operação, reinicializá-lo com uma configuração padrão/segura.
2. Suporte a níveis de qualidade de serviço (*Quality-of-Service*, QoS) diferenciados, em conformidade com o grau de criticidade da operação/comunicação.
3. Unidades de comunicação auto-contidas: todos os elementos necessários para sua operação independente estão presentes (i.e., MCU, rádios (principal e WuR), armazenamento secundário, unidade de bateria).
4. Auto-agregável: uma única central de monitoramento pode conter múltiplas unidades regulares de comunicação sem a necessidade de conexões cabeadas entre as unidades e a unidade controladora. Assumindo, por exemplo, que a unidade controladora encontra-se dentro de uma caixa hermética, a inclusão de uma nova unidade de comunicação requer simplesmente que esta seja largada dentro da caixa principal. A manutenção (inclusão ou exclusão de unidades) é simples e rápida.

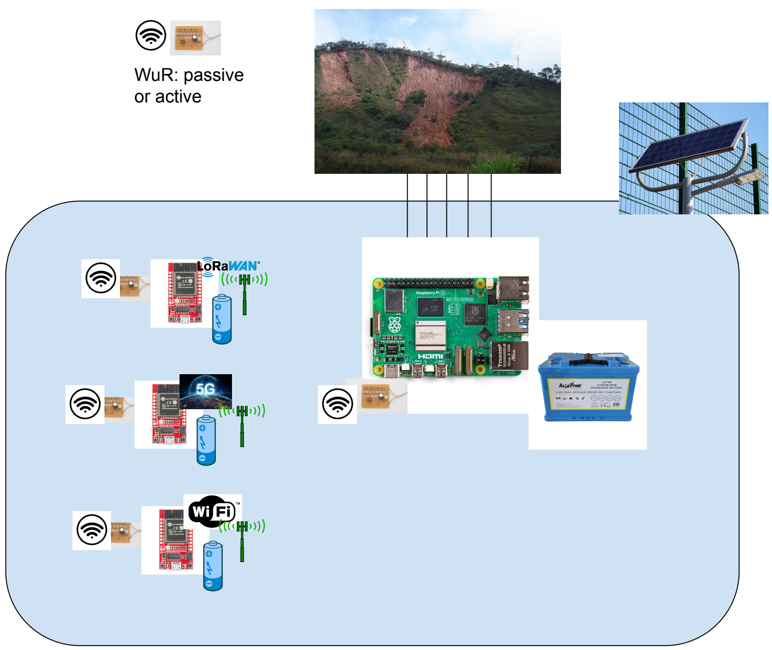

Figure 1: Esquema simplificado de um sistema hierárquico de comunicação ativados por WuRs

A ativação das unidades de comunicação ocorre via WuR (passivo ou ativo), garantindo consumo de energia quase nulo em modo de inatividade (i.e., com rádio passivo). Esta modalidade de ativação se torna viável mesmo com rádio passivo, considerando-se a proximidade física entre os dispositivos. Adicionalmente, não exige conexões cabeadas (ou via barramento) entre as unidades, além de conferir um grau flexível de tolerância a falhas.

Como parte do mecanismo de *health-check*, pode-se adotar a estratégia de reinicialização (i.e., *reboot*) baseada em uma imagem confiável e estável do *firmware*. Como uma funcionalidade avançada, pode-se adotar a estratégia de atualização do *firmware* empregando *hardware* com suporte a *Trusted Execution Environment* (TEE) [3, 7] como, por exemplo, *Trust Zone* para CPUs baseadas na arquitetura ARM, ou SGX para sistemas baseados em Intel™. A carga e inicialização da aplicação principal também pode ocorrer via TEE, incrementando ainda mais os requisitos de segurança. Inclusive, isto pode viabilizar a atualização da aplicação, via Internet, a partir de servidores seguros/confiáveis.

Para garantir redundância, e um grau flexível de tolerância a falhas, as unidades são auto-contidas e são ativadas e desativadas sob demanda via WuRs (passivos ou ativos). Quando a sinalização parte de outra unidade (ou coordenador), dada a proximidade física, tem-se duas variáveis controladas e previsíveis no processo de inicialização: consumo de energia e latência. No caso de se empregar rádios passivos, a energia mínima e o atraso podem, facilmente, ser estimados com a equação de Frii [2]. Tem-se, portanto, um ambiente com um grau de controle determinístico.

2.1 Protótipo

Considerando-se aspectos de *hardware*, pode-se adotar os seguintes dispositivos na elaboração de um protótipo do sistema pretendido:

- Como unidades de comunicação, Single Board Computers (SBCs) baseadas no ESP-32, equipadas com unidades de comunicação LoRA, WiFi e rede celular (e.g., 4G, 5G).
- Como unidade controladora: Raspberry Pi.
- Como WuR: Texas CC-1200.
- Comunicação local (interna, entre coordenador e unidades de comunicação): Bluetooth (BLE) ou WiFi local.

Quando a aquisição de WuRs for um empecilho devido a limitações orçamentárias, pode-se adotar outros mecanismos para acordar as unidades de comunicação como, por exemplo, ativação via Bluetooth (e.g., *Wake-on-Bluetooth* [1]).

[1] `https://forum.arduino.cc/t/how-to-wake-up-an-arduino-by-bluetooth-solved/105319`

2.2 Elementos de *software*

Esta seção apresenta os aspectos arquiteturais do sistema em termos dos seus elementos de *software*.

Propõe-se a seguinte modalidade de comunicação interna (i.e., entre coordenador e unidades regulares) e organização da aplicação de coordenação (vide Figura2):

- Estruturar toda a comunicação (controle e dados) entre coordenador e unidades empregando o protocolo MQTT [5].
- No controlador (e.g., Raspberry Pi) instanciar um servidor MQTT (e.g., Mosquitto).
- Após ativação das unidades regulares, a comunicação entre estas e o coordenador pode ocorrer via Bluetooth, WiFi ou qualquer outra opção disponível em ambas as plataformas de *hardware* empregadas para hospedar o coordenador e as unidades de comunicação.
- Quando uma unidade regular é acordada, esta conecta-se ao servidor MQTT no controlador e, a partir daí, recebe todas as mensagens dos tópicos assinados. Em sequência, pode-se dar início à comunicação da unidade com o mundo externo. Esta pode ser também via MQTT com um servidor externo, empregando-se a interface de comunicação padrão da unidade (e.g., LoRA, 4G/5G, WiFi).

O protocolo MQTT suporta comunicação assíncrona a nível de aplicação. Ou seja, mensagens enviadas enquanto o cliente estiver desconectado são mantidas armazenadas no servidor/Broker; quando o cliente realizar nova conexão, essas mensagens são enviadas a ele. Para que isso ocorra, deve-se empregar um nível de qualidade de serviço específico (i.e., QoS 1 ou 2) e solicitar que a sessão do cliente seja na modalidade persistente (i.e., *non-clean session*)

Define-se a seguinte nomenclatura de tópicos de controle e dados:

- Tópicos de controle (/Control):
  - */Control/WakeUp/Mode*: Mode pode ser Uni, Multi ou Broad. O conteúdo da mensagem apresenta a informação necessária acerca de quem deve ser acordado. Quando Uni (um determinado nó alvo), a mensagem contém o ID da unidade a ser acordada. Exemplo: "/Control/WakeUp/Uni", contendo como mensagem "Unit1", determina que somente a Unit1 deve ser acordada. Quando Multi (um grupo de nós), designa uma lista de nós a serem acordados. Exemplo: "/Control/WakeUp/Multi", contendo como mensagem "Unit1, Unit2", designa que as unidades Unit1 e Unit2 devem ser acordadas. Quando Broad, todas as unidades devem ser acordadas (a mensagem pode ser vazia). **Clientes: Assinante(s): Controlador ; Publicador(es): Controlador e/ou Aplicação de monitoramente.**

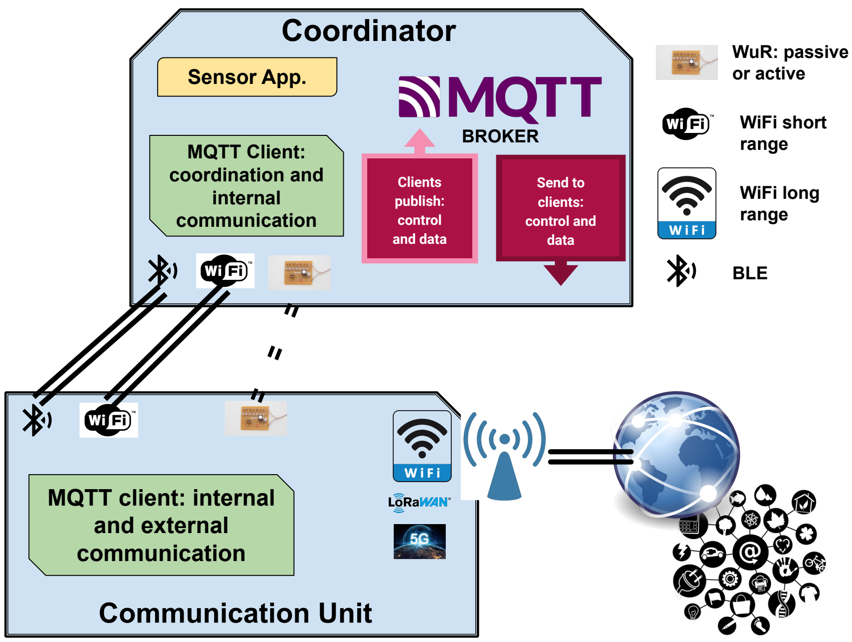

Figure 2: Arquitetura da aplicação

- */Control/Configure/[Unit]*: Tópico de configuração das unidades. Unit especifica o endereço da unidade (i.e., há um tópico para cada unidade endereçada no sistema). Aqui especifica-se as mensagens segundo um padrão a ser melhor detalhado, permitindo-se incluir novos tipos à medida que houver necessidade. **Clientes: Assinante(s): unidade alvo; Publicador(es): coordenador.**
- */Control/Configure/Coordinator*: Tópico de configuração do coordenador. Formato e tipos de mensagens a serem definidos. **Clientes: Assinante(s): coordenador; Publicador(es): aplicação de monitoramento ou gerenciamento.**
- */Control/Error*: Tópico para tratamento de erros referente a controle. Mensagem (a ser definida) deve conter todas as informações pertinentes ao erro a ser notificado/tratado.

- Tópicos de dados (/Data):
  - */Data/To/[Unit]*: Tópico de envio de mensagens (formato a ser definido) para a unidade. Unit deve ser o ID da unidade destino. **Clientes: Assinante(s): unidade alvo; Publicador(es): coordenador.**
  - */Data/From/[Unit]*: Tópico de recepção de mensagens da unidade. Unit deve ser o ID da unidade origem. **Clientes: Assinante(s): coordenador; Publicador(es): unidade origem.**
  - */Data/Coordinator/(data + instructions)*: Tópico para comunicação da aplicação de sensoriamento com o coordenador. Conteúdo da mensagem (a ser definida) contém dados e instruções. **Clientes: Assinante(s): coordenador; Publicador(es): aplicação de sensoriamento ou gerenciamento.**
  - */Data/Error*: Tópico para tratamento de erros referente a dados. Mensagem (a ser definida) deve conter todas as informações pertinentes ao erro a ser comunicado/tratado.

A Figura 3 ilustra o arcabouço principal da aplicação, seus principais elementos, threads, procedimentos e tópicos de dados e controle.

2.2.1 Aplicação de sensoriamento

Prevê-se os seguintes elementos de *software* como parte da aplicação principal de sensoriamento:

- InitSensorApp(): procedimento de inicialização da aplicacação de sensoriamento;
- Event(data, type): quando ocorrer um evento relacionado ao fenômeno monitorado (e.g., deslocamento de solo), o mesmo é notificado via uma mensagem contendo os dados (i.e., *data*) correspondentes ao evento bem

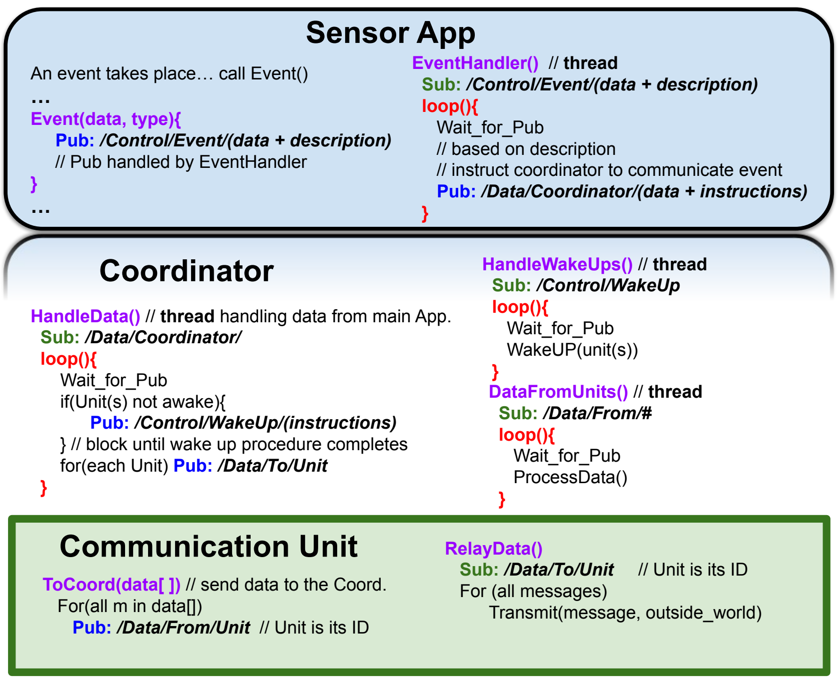

Figure 3: Arcabouço principal da aplicação: elementos, *threads*, procedimentos e tópicos de dados e controle

como o tipo (i.e., *type*) de tratamento (e.g., prioridade, unidade(s) de comunicação responsável(eis) pela transmissão ao agente externo). Efetivamente, essas informações são encaminhadas via o tópico de controle **/Control/Event**.

- EventHandler(): thread específica para tratar os eventos. **Assina o tópico /Control/Event**. A thread aguarda em um laço contínuo para tratar ocorrências de novos eventos. Quando os dados estiverem prontos para transmissão, **publica eles via o tópico /Data/Coordinator**

2.2.2 Coordenador

- HandleData(): *thread* responsável por tratar os dados provenientes da aplicação principal. **Assina o tópico /Data/Coordinator**. Aguarda em um laço contínuo por dados a serem comunicados às unidades de comunicação. Caso a unidade destino não esteja ativa, inicia os procedimentos de ativação da unidade publicando instruções correspondentes no tópico **/Control/WakeUp**. Quando a unidade estiver ativa e pronta, publica os dados no tópico alvo correspondente (i.e., **/Data/To/Unit** com o ID correspondente à unidade alvo).

- HandleWakeUps(): *thread* responsável por tratar comandos de ativação de unidades. Assina o tópico **/Control/Wakeup**, aguardando em um ciclo contínuo por solicitações de ativação de unidades de comunicação. Fica transparente o mecanismo efetivo de acordar a unidade alvo, privilegiando-se tecnologias/mecanismos que apresentam baixo consumo de energia (e.g., WuRs).

- DataFromUnits(): *thread* responsável por tratar dados advindos das unidades de comunicação. Assina o tópico **/Data/From/#** (i.e., pode receber dados de todas as unidades via este único tópico). O tópico funciona como um canal de comunicação através do qual as unidades podem, por exemplo, reportar erros, requisitar serviços e comunicar novas funcionalidades disponíveis na unidade (e.g., novos tópicos criados sob demanda).

2.2.3 Unidades de comunicação

- InitUnit(): inicialização da unidade;

  - Sleep([..]): após inicialização, a unidade permanece em estado de dormência (i.e., sleep mode), mantendo em execução apenas o dispositivo responsável pela ativação remota (e.g., WuR). Pode-se, também, adotar uma abordagem estilo *duty cycle* programando a unidade para reativações periódicas. O coordenador pode configurar esse procedimento durante o processo de inicialização ou sob demanda via instruções publicadas no tópico de controle da unidade.

- WakeUpHandling(): tratamento do processo de ativação, incluindo a inicialização do modo/protocolo de comunicação. Depois de acordar, conecta ao broker e acessa todas as publicações recebidas no tópico **/Data/To/Unit** (dados que devem ser comunicados a um ou mais agentes externos).
- RelayData(): um procedimento para retransmitir dados recebidos do coordenador via o tópico **/Data/To/Unit**.
- ToCoord(): um procedimento para enviar dados ao coordenador, via publicações no tópico **/Data/From/Unit** (Unit contém a identificação da unidade).

3 Conclusões e trabalhos futuros

Neste documento apresentamos a proposta de uma arquitetura de comunicação, baseada na diversidade de protocolos, para sistemas de monitoramento e prevenção de deslizamentos de terra. A arquitetura é agnóstica a tecnologias de comunicação, atuais ou futuras. A orquestração entre os elementos presentes na arquitetura dá-se via um protocolo de aplicação (i.e., MQTT) público e com diversas implementações de código livre, sendo muitas destas empregadas em sistemas de produção na academia e na indústria.

Este documento apresenta também orientações para o desenvolvimento de uma plataforma de prova de conceito. A proposta prevê baixo custo de implementação, pois recomenda dispositivos comumente empregados na prototipação de sistemas e aplicações em IoT. Em trabalhos futuros, planejamos dar continuidade a essa pesquisa contemplando um primeiro estudo de caso experimental.

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Apêndice C

Convite visita ao CEMADEN

Convite

Prezados Professores
Dr. Jo Ueama
Dr. Caetano Mazzoni Ranieri
Dr. Marco Spohn

Venho convidá-los a participar de uma reunião presencial no Cemaden/MCTI, situado no Parque Tecnológico de São José dos Campos/SP, Estrada Dr. Altino Bondesan, 500, sobre as temáticas abaixo elencadas:

(1) The potential of in-situ Near-infrared spectroscopy (NIRS) instrumentation applied to mass movement - preliminary laboratory results.

(2) Empirical Investigation of magnetic induction based instrumentation for multiple-layer soil-moisture measurements of large volumes of soils.

(3) Introducing Dormant Wireless Sensor Networks for Disaster Monitoring Applications.

São José dos Campos/SP, 10 de maio de 2024.

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