On the Impact of Overcoming Wake-up Radio Limitations on the Performance of Energy Aware Routing in Wireless Sensor Networks

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***Abstract*—The integration of *Wireless Sensor Networks* (WSNs) with the *Internet of Things* (IoT) has significantly broadened the scope of interconnected devices, offering novel solutions and enhancing capabilities in monitoring and control across various sectors. Despite remarkable advancements, reliance on battery-powered wireless devices introduces significant challenges, primarily due to energy constraints that limit the operational lifespan of these networks. This paper addresses these challenges by exploring the efficacy of *Wake-up Radio* (WuR) technology as a means to enhance energy efficiency. WuR technology allows nodes to remain dormant until communication is necessary, thereby extending the network lifetime without compromising performance. However, limitations such as reduced communication range and data transmission rates pose obstacles to the full realization of WuR potential. Through simulation-based experiments, this study evaluates the performance of a novel protocol, *Simple Energy Aware Routing* (SEAR), under various WuR configurations, using the *GreenCastalia* simulator. Our findings demonstrate how optimizing WuR parameters can significantly impact key network performance metrics, suggesting pathways for future WuR technology development to achieve optimal WSN performance within the IoT paradigm. The insights provided aim to inform ongoing research efforts, contributing to the evolution of WSNs as a foundational element of the IoT infrastructure.**

I. INTRODUCTION

The pervasive nature of wireless technologies and embedded systems, combined with the evolution of networking paradigms such as *Wireless Sensor Networks* (WSNs), has ushered in an era of highly interconnected networks. These networks offer unprecedented control and monitoring capabilities across diverse environments. They also provide the foundation infrastructure for the *Internet of Things* (IoT), which integrates the vastness and flexibility of the Internet with WSNs across the globe [1].

While the IoT revolutionizes potential solutions and opportunities, it also faces familiar constraints. A notable challenge within popular IoT deployments is the reliance on wireless devices powered by finite energy sources. These devices are often compact, battery-operated, and placed in locations where battery replacement or recharging is difficult or impossible. Thus, the battery life dictates the operational lifespan of both individual nodes and the entire network. To address this critical limitation, there's a push towards developing solutions focused on energy efficiency across the protocol stack and node design. A leading strategy in energy optimization, achieving alignment with application demands, involves adopting *Wake-up Radio* (WuR) technology [2]. WuR-equipped nodes feature an additional ultra-low-power radio, the WuR receiver, which remains active to receive wake-up signals, while the main radio stays off to conserve energy. Nodes can be awakened by signals that match predefined *wake-up addresses*, significantly reducing energy usage compared to traditional methods, like duty cycling [3]. Another advantage is that using WuRs avoids the latency penalties of duty cycling [4]. Overall, WuR-enabled networks demonstrate significantly enhanced performance, with lifetimes extending to decades, far surpassing the few months typical of duty-cycled networks [3], [5].

However, WuR technology does have its constraints, particularly regarding **communication range** and **data transmission rates**.

- **Communication Range**: Modern WuR implementations typically fall short in communication range compared to main radios, often not exceeding a few tens of meters [6], [7]. This limitation can lead to inefficient network paths, increasing energy usage and introducing latency.
- **Data Transmission Rates**: WuR technologies generally offer lower data rates to maintain low energy consumption, seldom surpassing 10 kbps [2], [8], [9] This constraint, while energy-efficient, may increase the likelihood of interference and communication failures.

Ongoing research efforts are directed at enhancing WuR receivers to preserve low energy consumption while improving both range and data rates, addressing the outlined limitations. For instance, innovations in RF Micro-electromechanical Systems (MEMS) have shown potential for WuRs with minimal power usage, extended range, and increased data rates [10], [11], [12]. These recent efforts and advances prompt inquiries into whether and how these promising new WuR systems affect the performance of WSNs. Therefore, it is essential to evaluate their impact on the advancement of WuR technology and, more broadly, on the development of WSNs as a core element of IoT infrastructure.

This paper explores the impact of advanced WuR designs on network performance through simulations, keeping the power consumption very low, and varying range and data rates beyond current capabilities. Specifically, we consider WuR ranges starting from values experimentally determined with current prototypes (e.g., 15 to 25 m [3], [6]) to values at par with common main radio ranges (around 70 m). The data rates we consider start from those that are currently available ($\leq$ 10000 bps) and go as high as 10 Mbps. Our analysis considers the performance of networks tasked with key operations, such as *data collection via routing*, wherein data packets are transported from an originating node to a set collection node via a multi-hop path. To this aim, we introduce a new routing protocol, called *Simple Energy Aware Routing* (SEAR), designed for efficient data collection and routing in WSNs, and evaluate its performance under varying network and WuR parameters using the *GreenCastalia* simulator [13]. Several aspects of both a typical sensor mote and of an exemplary WuR receiver are modeled in details, considering both compute and communication characteristics, including their energy consumption and induced delays. SEAR solely focus on energy efficiency and is implemented by simple operations, ensuring that the performance evaluation arises from varying network and WuR parameters and characteristics rather than from protocol-dependent design and optimization. We investigate key performance metrics such as packet delivery ratio, latency, energy consumption, and overall network lifespan. Our findings underscore that increasing the data rate of WuRs notably reduces the likelihood of collisions and transmission delays, thereby enhancing the packet delivery ratio and reducing latency. Similarly, expanding the communication range of WuRs helps in reducing the number of hops needed to route data to the sink, which directly contributes to lower latency and energy consumption, thus extending the network's operational lifespan. However, our results also highlight a nuanced trade-off between range extension and energy efficiency. While longer ranges can decrease the number of transmission events, they potentially increase the number of nodes woken up unnecessarily, thereby increasing overall energy expenditure. Therefore, optimal design of WuR systems must carefully balance range, data rate, and power consumption to achieve the best overall network performance.

The remainder of the paper is structured as follows. Section II describes the WuR-based network scenarios and current WuR limitations. In Section III we introduce the SEAR protocol. Section IV discusses the impact of overcoming WuR limitations on network performance. Related works are reviewed in Section V. Section VI provides concluding remarks.

II. WuR-BASED NETWORK SCENARIOS

We consider wireless networks made up of nodes with a *main radio* for data transmission and with a *wake-up radio* (WuR) for energy saving purposes. One of the network nodes is designated as the *edge router*, also called *data collector* or *sink* in the following. The sink is the destination of the data packets generated by all the other nodes in the network. We stipulate that the sink has no energy restrictions (e.g., it is plugged into the grid, or has provisions for energy replenishment in time). Data are typically generated by applications based on on-board sensors. When information is produced, a corresponding data packet is created that is routed to the sink. To show the effect of WuRs with different characteristics on the performance of data gathering protocols, we consider networks that are fully connected with respect to both WuR and main radio. For each data packet generated at any of the nodes in the network, there is always at least one route to the sink formed by nodes that can wake each other up.

Data packets are exchanged between nodes by using their main radios. The process consumes a considerable amount of energy, commonly in the realm of milliWatts [14], regardless of whether nodes are transmitting data, receiving data, or merely waiting to receive data (*idle listening*). This energy consumption can be attenuated by the use of WuR technology, whose receivers consume orders of magnitude less than main radio receivers (e.g., μWatts or less [2], [3], [15]). A WuR-enabled node with no data to transmit enters an *asleep state*, wherein its main radio is turned off. In this state its WuR receiver stays on, awaiting for wake-up signals. When a node has one or more packets to transmit, it needs to choose one or more forwarders towards the sink. This selection follows the rules of the specific routing protocol used in the network. The sender *awakens* by turning on its main radio, transitioning to an *awake state*. Since the sender's neighbors that can act as forwarders are possibly asleep, the sender uses its WuR to awaken them. To this aim, it transmits a *wake-up sequence* (WuS) over the WuR. Upon receiving the WuS, a receiver decides whether or not it can serve as a relay of data packets from the sender. This is done by checking if the WuS matches any *wake-up address* (WuA) of the receiver. Nodes can have a set of WuAs, and if any of them match the received WuS, the node transitions to the awake state, turning its main radio on. One or more of the awakened nodes are then selected as relays, after which data communication happens via the main radio. The process may repeat, with selected receivers becoming senders and their neighbors becoming the new receivers. This way, packets are routed across the network by awakening nodes *on-demand*. Nodes that are not participating in the routing of a packet stay asleep, conserving energy.

Despite offering significant benefits, current WuR technology has severe limitations that impose appreciable constraints on network operation and performance. In the remainder of this section we discuss the limitations of WuR technology and indicate ways to overcome them, some of which we investigate further in the rest of the paper.

A. WuR Limitations

Current WuR technology limitations include *very low data rates* and *short ranges*, both stemming from the need to keep the WuR energy consumption very low.

The data rate of a WuR is usually at least one (but most commonly two) order(s) of magnitude lower than that of the main radio. Current designs and prototypes, for instance, allow for the transmission of a WuS at rates in the order of few kilobits per second (rarely beyond 10 kbps), while main radios communicate in the hundreds (e.g., ZigBee) or thousands (e.g., WiFi) of kilobits. (This is one of the reasons why, while it is possible to forward data packets via the WuR, it is exceedingly impractical, especially for data packets whose size exceeds a few bytes.) So, while the use of WuR technology circumvents the significant latency penalties of duty cycling, the low data rate still imposes a bottleneck on latency and increases the likelihood of interference on the WuR channel. For instance, the nominal time that a WuR would need to transmit a WuS of 8 b at 1 (5) kbps is 8 (1.6) ms. This is the same amount of time that a main radio operating at 250 kbps needs to transmit large data packets, of size 250 (50) B. The limitation of WuR data rate can be amortized by keeping WuSs as short and infrequent as possible. This, however, might hinder the advantage of using WuR technology for energy conservation and better network performance. This motivates us to explore WuR technology for low power, high-speed data rates.

Similarly, the range of the WuR is typically a fraction of that of the main radio [6]. This can prevent a node from directly awakening a neighbor that is nearer to the sink or, in general, better suited to be a forwarder, resulting in longer routes, with detrimental consequences on performance. Fig. 1 illustrates the problem, depicting a simple topology of 5 nodes.

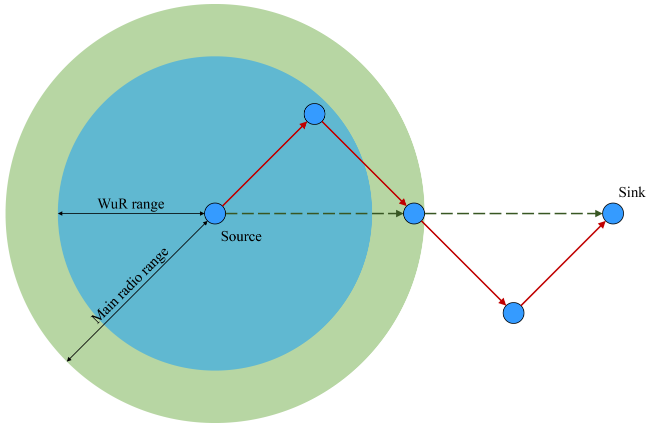

Fig. 1. Range differences between WuR and main radios impact route lengths.

Packets must travel from the source to the sink. Routing would be dictated by the main radio, allowing for the packet to reach the sink in just 2 hops (dashed green arrows). However, when using the WuR, the intermediate nodes are asleep until awoken. Thus, the solid red arrows indicate how the packet would be forwarded by awakening nodes. Here, the packet takes 4 hops to reach the sink. Solutions include relaying the WuS to awaken only distant nodes or using ultra-low power WuR with ranges similar to the main radio. The first solution is ideal when the forwarder is pre-selected, as in static or tree-based routing like the redesigned Collection Tree Protocol (CTP) [16] for WuRs. Its benefits have been explored for two hop wake-up relaying [17] and for multi-hop relaying [18]. The second solution is investigated here.

III. SEAR: Simple Energy Aware Routing

To showcase the use of WuR technology and to investigate the network performance that can be achieved by overcoming its key limitations, we introduce a WuR-enabled routing protocol whose path selection is guided by the energy available on the way to the sink. This protocol is exemplary of energy efficient routing for WSNs with WuR-enabled nodes, including Green-WUP [19] and GreenRoutes [20].

The SEAR protocol operates on multiple layers, with nodes performing relay selection and channel access concurrently. Relay nodes are selected based on the number of hops to the sink and on the node energy levels on the path to the sink. To jointly obtain WUR-based and energy efficient relay selection, nodes are assigned *semantic* WuAs [19], [21], [22].

A. Network Scenario and Notation for SEAR

We consider networks with N WuR-enabled nodes statically scattered in an $L \times W$ area. All network topologies are fully connected by WuR links. The sink is placed in one of the corners of the deployment area.

Every node n keeps a record of the minimum number of hops h_n to the sink. Each node also keeps a record of the amount of energy in its battery, the *node energy level* e_n. This value is discretized and represented by a whole number in the range $[0, k]$. Nodes also track the energy on the path to the sink through neighbors that are one hop nearer to the sink. Given the neighbors m of node n such that $h_m = h_n - 1$, the *path energy level* ϵ_n is recursively defined as the highest among the values of $\min(e_m, \epsilon_m)$. These values are communicated to node n by each neighbor m in the headers of control and data packets exchanged among neighbors. (The path energy level of the sink is considered a very high number, namely, the sink is assumed not to be energy constrained.)

Fig. 2 shows how ϵ_n is determined by each node n.

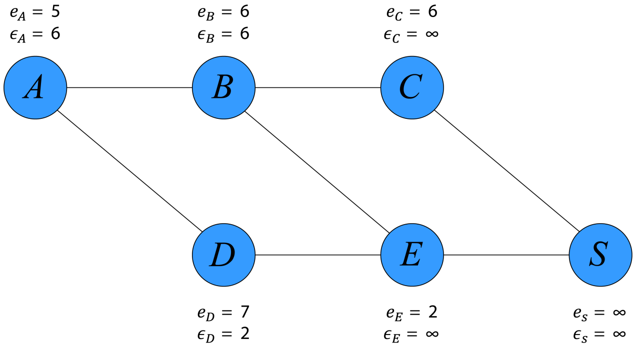

Fig. 2. Determining path energy levels ϵ_n.

Nodes C and E are one hop away from the sink S. While they both have finite node energy levels, their path energy levels are infinite, as any packet received by either node has to be forwarded to the sink. Next, node D has only one next-hop neighbor in E. The path energy level of D is set as the minimum between $e_E = 2$ and $\epsilon_E = \infty$. Thus, $\epsilon_D = 2$. After that, node B has two possible paths to S, via E or C. The path energy level via E is 2, as previously determined for D. The path energy level via C is the minimum between $e_C = 6$ and $\epsilon_C = \infty$, which is 6. Between these two path energy levels, the higher is that via C, which means that $\epsilon_B = 6$. Finally, A has three possible paths to the sink, but only two next-hop neighbors: D and B. Via D, the path energy level is the lower between $e_D = 7$ and $\epsilon_D = 2$, which is 2. Via B, the path energy level is the lower between $e_B = 6$ and $\epsilon_B = 6$, which is 6. The higher of the two is via B, so $\epsilon_A = 6$. Notice that, despite D having more node energy than B, the selected path is via B (and subsequently, C), as the minimum node energy level along this path is the highest across all possible paths. At network set-up, the values of h_n and ϵ_n are determined for all nodes. This is done by a WuR-based broadcast protocol initiated by the sink, and possibly repeated throughout the network lifetime to deal with node outages [19], [18]. After the set-up operations are completed, nodes are by default in their asleep state, with their main radio off. In order to receive a packet, a node must first be awoken by receiving a WuS that matches its WuA. For SEAR, every node n has a semantic WuA that is the concatenation of the binary representations of h_n and $\min(e_n, \epsilon_n)$, $[h_n, \min(e_n, \epsilon_n)]$.

B. Packet Forwarding

When a node n has a packet to be routed to the sink it must select one of its neighbors $\hat{m}$ as a relay for that packet. To this aim, node n broadcasts a WuS on its WuR to awaken only those neighbors m that are both one hop closer to the sink and have the same path energy level of node n. This WuS is therefore $[h_n - 1, \epsilon_n]$. At this time, node n turns on its main radio and awaits to hear from its neighbors.

Every neighbor m receives the WuS and compares it to its own WuA. If the two match, then m awakens and broadcasts a clear-to-send (CTS) control packet on its main radio. In order to minimize the probability of CTS collisions, node m sends the CTS packet after a delay $\delta(m)$ [23]. Meanwhile, node n awaits for an incoming CTS. If no CTS is received before a timeout expires, then n revises its WuS by subtracting 1 from the path energy level and broadcasts it. This is repeated until it reaches 0, at which point the data packet is dropped. If instead node n does receive a CTS before the timeout expires, then it designates the sender of the CTS as the relay node $\hat{m}$. If node n receives more than one CTS, it ignores all but the first. Once $\hat{m}$ is selected, node n uni-casts the data packet to $\hat{m}$ on its main radio. Any awakened neighbor m that hears the data packet transmission first checks the incoming header destination field. The node m for which $m = \hat{m}$ remains awake and receives the entire data packet; every other node m goes back to sleep. This reduces the time spent awake and the subsequent energy consumed. It also prevents neighbors from sending additional CTSs, reducing the likelihood of collisions. Once $\hat{m}$ receives the data packet, it responds with an acknowledgement (ACK) packet. Upon receiving the ACK, n goes to sleep. At this point, the forwarding is complete. Further details and examples can be found in [23].

IV. PERFORMANCE EVALUATION OF NETWORKS WITH WURS WITH DIFFERENT DATA RATES AND RANGES

We evaluate network performance for different WuR data rates and ranges by implementing SEAR in the *GreenCastalia* simulator [13], an extension of the *Castalia* simulator [24] based on the OMNeT++ framework [25]. We consider the MagoNode++ mote and the WuR prototype described by Spenza et al. to model WuR-enabled network nodes [3]. *GreenCastalia* has been modified to implement their characteristics. Particularly, our model for the WuR receiver incurs very low energy consumption, namely, around 1.3 μW [3], independently of the data rate and range that we simulate.[1] Nodes broadcast WuSs via a low-power CC1101 transceiver (by Texas Instruments) [27]. This transceiver operates below 1 GHz and supports the use of *On-Off Keying* (OOK) modulation. Additionally, we model the power-consumption of waking up by WuA via integrated ultra-low-power PIC12LF1552 microcontrollers (by Microchip [28]). When idle, power consumption is 0.036 μW. When active, power consumption is 54 μW. The MagoNode++ and the WuR are powered by one AA lithium-ion battery with 800 mAh and a nominal voltage of 3.7 V. Our battery model allows the simulator to precisely estimate the energy consumption at different points of the node's operation. This includes the passive energy decay of the battery, the rate of power consumption by each radio when idle, the power for transmission and reception, and the power consumed by on-board sensors and processor. Characteristics and parameters of the MagoNode++ are based on real life experiments.

A. Scenarios and Parameters

In our experiments, the N nodes are scattered in an area that is 224×56 m^2. Each node is powered by energy storage with capacity 10656 J. Data packets are generated at an average of λ packets per second, following a Poisson distribution. When a packet is generated, one of the network nodes (except the sink) is selected randomly and uniformly to be its source. Data packets are 70 B in size, which includes headers and payload. The main radio has its transmission power fixed at -2 dBm, with its transmitter consuming 31.2 mW and its receiver consuming 33.6 mW while active. Its channel data rate is set to 250 kbps and the range is set to 70 m. CSMA is used at the MAC layer. WuSs and WuAs are 8 bits in size. The WuR has its transmission power fixed at 10 dBm, with its transmitter consuming 90 mW and its receiver consuming 1.071 μW while active.[2] Its data rate is set to d kbps and its range is set to r m. For both main radio and WuR we use an

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[1] Current wake-up radio design for WSN and IoT-like devices achieves even lower energy consumption, down to the nW [26]. These WuRs, however, obtain ranges and data rates comparable to those of the design and prototype considered in our work, and usually do not consider WuA-based addressing. Future wake-up radios, such as those based on RF MEMS [10], promise ultra-low energy consumption with ranges and data rates as those envisioned here. These new designs motivates us to keep low consumption figures while varying WuR ranges and data rates among values that are worth investigating.

[2] These values are consistent with those measured experimentally on our prototypes of the MagoNode++ and of the WuR.

additive interference model for determining concurrent transmissions from multiple nodes, namely, to detect interference and decide whether a transmission is successful or not.

The key parameters N, λ, d and r are varied as follows:

1) Network size $N \in \{48, 64, 128\}$
2) Data traffic $\lambda \in \{2.5, 7.5, 12.5\}$
3) WuR data rate $d \in \{1, 10, 100, 1000, 10000\}$ kbps
4) WuR range $r \in \{15, 18.75, 25, 37.5, 75\}$ m

Parameters 1 and 2 represent the scale of the network (specifically, size and traffic). By varying parameters 3 and 4 we investigate the impact of overcoming the fundamental limitations of WuRs (Section II-A). The power consumption values for d of 1 kbps and 10 kbps have been measured in actual WuR prototypes [3]. Power consumption values for WuR ranges of 15 and 18.75 have also been experimentally obtained [6]. We maintain these power values for all other data rates and ranges results. Table I summarizes all simulation parameters.

TABLE I
GENERAL SIMULATION PARAMETERS.

PARAMETER	VALUE
Constants:	
Network area	224×56 m^2
Node energy storage	10656 J
Data packet size	70 B
Main radio:	
Transmission power	-3 dBm
Power consumption:	
Transmitter	51.9 mW
Receiver	65.4 mW
Channel data rate	250 kbps
Range	70 m
WuS/WuA length	8 b
WuR:	
Transmission power	10 dBm
Power consumption:	
Transmitter	90 mW
Receiver	1.071 μW
Variables:	
Number of nodes [N]	$\{48, 64, 128\}$
Packets per second [λ]	$\{2.5, 7.5, 12.5\}$
WuR:	
Data rate [d, in kbps]	$\{1, 10, 100, 1000, 10000\}$
Range [r, in m]	$\{15, 18.75, 25, 37.5, 75\}$

SEAR-*specific Parameters*. SEAR uses lightweight control packets (CTS, ACK) that are 6 B in size. The maximum CTS delay $\delta_{\max}$ is set to 15 ms. Timeouts for response (after which the transmission is considered failed) are 30 ms for a WuS, 15 ms for a CTS, and 15 ms for a data packet. Failed data packet transmissions are retried a maximum of 15 times. In this network scenario, the maximum number of hops by the WuR is 16, which can be represented by 4 bits in the WuS. The other 4 bits are used to represent up to 16 energy levels, which makes $k = 15$. Table II summarizes the SEAR parameters.

TABLE II
SEAR-SPECIFIC SIMULATION PARAMETERS.

PARAMETER	VALUE
Control packet size	6 B
Maximum CTS delay ($\delta_{\max}$)	15 ms
Timeout for receiving response to:	
WuS	30 ms
CTS	15 ms
Data packet	15 ms
Maximum number of retries	15
Maximum number of WuR hops	16
Maximum energy level (k)	16

B. Performance Metrics

Performance is evaluated by measuring the following metrics (all averages).

- **Packet Delivery Ratio (PDR)** (%). This is the percentage of the data packets generated in the network that are successfully delivered to the sink.
- **End-to-end latency** (milliseconds). This is the amount of time required for a data packet to move from the source to the sink. This metric is computed only for data packets successfully delivered to the sink.
- **Energy consumption** (Joules). This is the average energy consumed per node, per hour.
- **Network lifespan** (hours). This is the amount of time that the network is operational, conservatively defined as the time when the first node dies because of energy depletion.

The collection of metrics ends at network lifetime (death of the first node). All results have been obtained by averaging the outcomes of a number of simulation runs large enough to obtain a 95% confidence interval and 5% precision.

C. Results

Our results examine the effects of varying each parameter on each performance metric. Results are depicted with certain parameters set at specified values.[3] Overall, the effects of network scale (N, λ) are as expected. Networks with more nodes have higher PDR and lifespans, and lower latency and energy consumption. Higher traffic imposes reduced PDR and lifespan, with increased latency and energy consumption.

1) ***Packet Delivery Ratio:*** The effect on WuR data rate and range on PDR are shown in Fig. 3 and Fig. 4, respectively.

Increasing WuR data rate d has a consistent, significantly positive effect on the PDR. Typically, the transmission time of WuSs is considerably higher than the transmission time of data packets, and are thereby far more likely to collide. The WuS transmission time reduces proportionally to increasing the WuR data rate. Thus, at higher data rates, it is less likely for WuSs to collide. Fig. 3 depicts the effects of d on the PDR, with $N = 128$ and $r = 18.75$ m. While the PDR is mostly high, the effects of data rate are more pronounced at higher levels of network traffic. For $\lambda = 12.5$, the PDR increases by approximately 34% as d goes from 1 kbps to 10000 kbps.

Increasing the WuR range has a mostly positive effect on PDR. At lower ranges, there are more forwarding events,

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[3] While results with other values are numerically different, we noticed that general trends and conclusions remain the same.

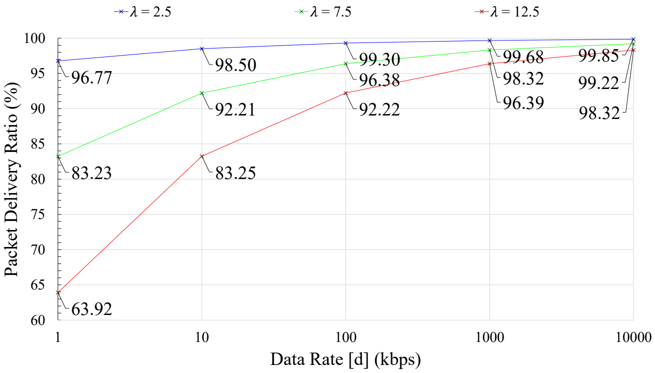

Fig. 3. Data rate d vs. PDR ($N = 128$ and $r = 18.75$ m).

which means that there are more opportunities for a packet to get dropped. However, at higher ranges, the likelihood of collisions increases, as is the case with most radios. Fig. 4 depicts the effects of r on PDR, with $N = 128$ and $d = 10$ kbps.

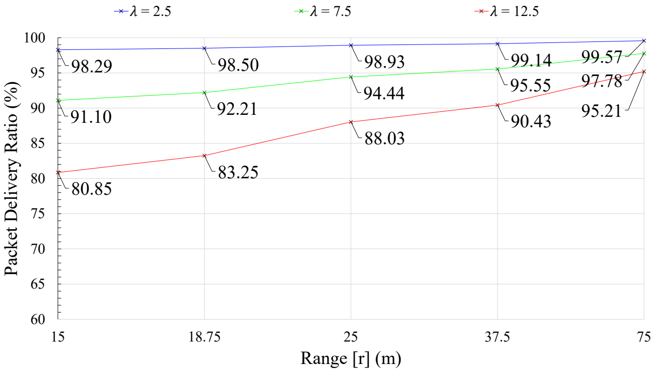

Fig. 4. Range r vs. PDR ($N = 128$ and $d = 10$ kbps).

For $\lambda = 12.5$, the PDR increases by approximately 14% as r goes from 15 m to 75 m. However, the effect is not always positive. Fig. 5 depicts the effects of r on PDR, with $n = 128$ and $d = 1$ kbps.

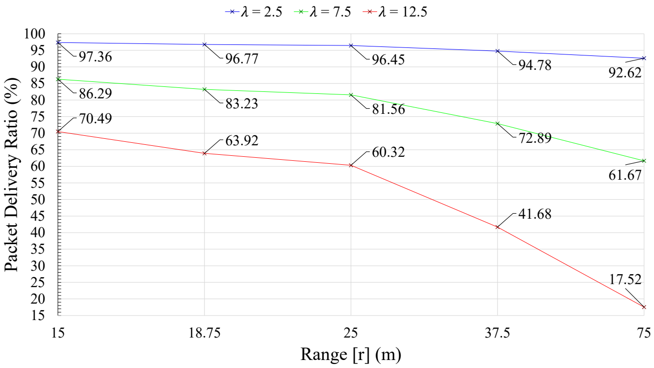

Fig. 5. Range r vs. PDR ($N = 128$ and $d = 1$ kbps).

Here, the trend is reversed, with the PDR at $\lambda = 12.5$ decreasing by approximately 53% as r goes from 15 m to 75 m. We observe that increasing the WuR range stops being detrimental and starts being beneficial for PDR at approximately $d = 3.6$ kbps.

2) ***End-to-end Latency:*** Results about varying WuR data rate and range on end-to-end latency are shown in Fig. 6 and Fig. 7, respectively.

Increasing the WuR data rate d has a consistent, significantly positive effect on end-to-end latency. This is due to WuS delivery time being the largest bottleneck for end-to-end latency. As data rate increases, the time to deliver a WuS decreases. Fig. 6 depicts the effects of d on end-to-end latency, with $N = 128$ and $r = 18.75$ m.

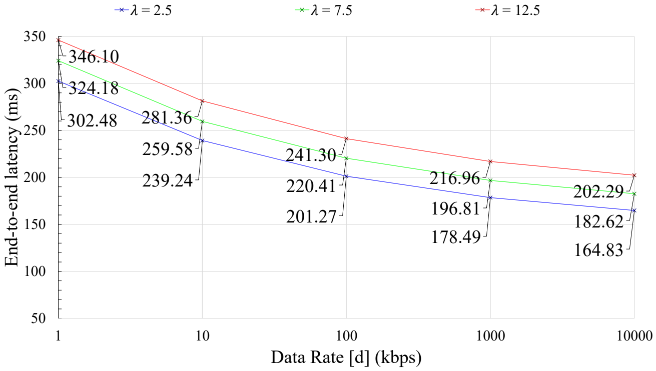

Fig. 6. Data rate d vs. end-to-end latency ($N = 128$ and $r = 18.75$ m).

The effects of network traffic are relatively similar across all data rates. For $\lambda = 12.5$, latency drops by over 153 ms as d goes from 1 kbps to 10000 kbps.

Increasing the range of the WuR also has a significantly positive effect on end-to-end latency. As range increases, the number of hops to the sink decreases. Fewer hops means less time spent relaying WuS (and data). (This effect is capped at the range of the main radio, as the wake-up target cannot be outside that range.) Fig. 7 depicts the effects of increasing r on end-to-end latency, in networks with $N = 128$ and $d = 10$ kbps.

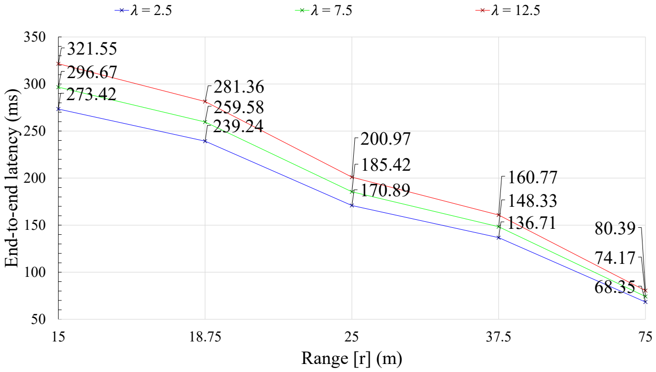

Fig. 7. Range r vs. end-to-end latency ($N = 128$ and $d = 10$ kbps).

Unlike with data rate, the latency for different levels of network traffic are not similarly proportioned across all ranges. As r approaches 75 m, the latency converges. This is because, at higher network traffic, SEAR makes proportionally greater use of the main radio, due to the probing and burst transmitting features. With proportionally less communication over the WuR, the benefits of increased WuR range are less pronounced. However, for lower levels of network traffic, the effects of increased WuR range are more pronounced.

*3) **Energy Consumption**:* Results concerning energy consumption for varying WuR data rates and ranges are shown in Fig. 8 and Fig. 9, respectively.

Increasing the WuR data rate has a visibly positive effect on energy consumption. The time spent transmitting WuSs is inversely proportional to the WuR data rate. The transmitter power consumption is fixed, the energy consumed by transmitting a WuS is directly proportional to the time spent transmitting that WuS. For this reason, the greatest effect on energy consumption is seen as d goes from 1 kbps to 10 kbps. Fig. 8 depicts the effects of varying d on energy consumption, with $N = 128$ and $r = 18.75$ m.

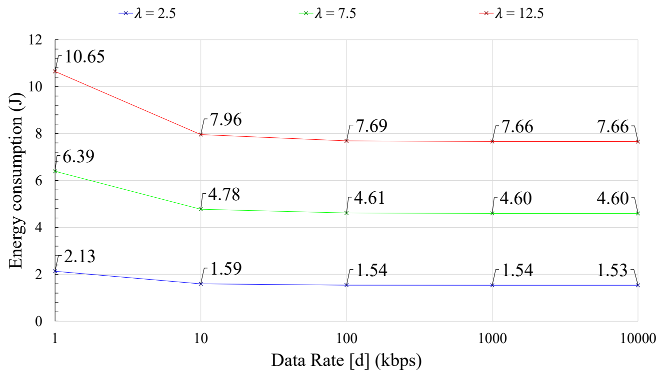

Fig. 8. Data rate d vs. energy consumption ($N = 128$ and $r = 18.75$ m).

For $\lambda = 12.5$, energy consumption reduces by approximately 2.69 J as d goes from 1 kbps to 10 kbps, but only reduces by approximately 0.3 J as d goes from 10 kbps to 10000 kbps.

Increasing WuR range has a negative effect on energy consumption. This is due to the effect of WuR range on node awakenings. The longer the WuR range, the more nodes on average are awakened by a broadcast WuS. However, longer WuR range also means fewer hops to the sink. So, at lower WuR ranges, there are more hops to the sink, but there are also fewer nodes awakened for each hop. Whereas, at higher WuR ranges, there are fewer, but more "expensive" hops, with more nodes being awakened by each broadcast WuS. This result in a non-monotonic trend for energy consumption. Fig. 9 depicts the effects of r on energy consumption, with $N = 128$ and $d = 10$ kbps. Energy consumption is highest at $r = 37.5$ m, and lowest at $r = 25$ m. For $\lambda = 12.5$, these values are approximately 8.36 J and 7.11 J respectively.

*4) **Network Lifespan**:* Fig. 10 and Fig. 11 concern the impact on network lifespan of varied WuR data rate and range.

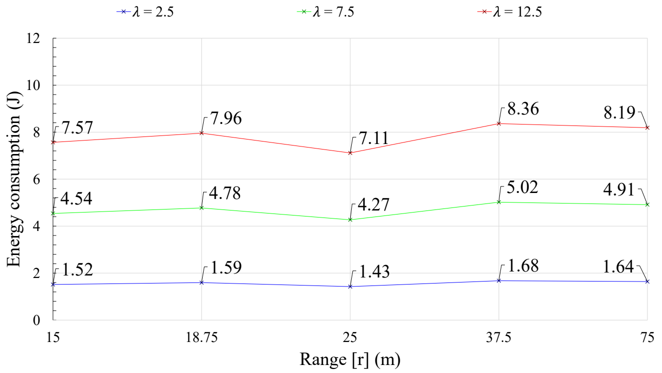

Fig. 9. Range r vs. energy consumption ($N = 128$ and $d = 10$ kbps).

Increasing the WuR data rate has a noticeably positive effect of network lifespan. Shorter transmission times at a constant transmission power consumption results in less energy consumed by WuS transmissions, allowing nodes to remain active for longer periods. Fig. 10 depicts the effects of d on network lifespan, with $N = 128$ and $r = 18.75$ m.

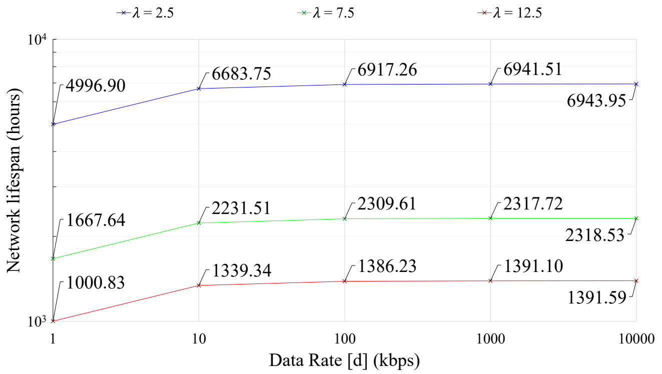

Fig. 10. Data rate d vs. network lifespan ($N = 128$ and $r = 18.75$ m).

Like with energy consumption, the greatest effect on network lifespan is seen as d goes from 1 kbps to 10 kbps. For $\lambda = 12.5$, network lifespan increases by approximately 338.5 hours. Whereas, at the same traffic, as d goes from 1000 kbps to 10000 kbps, network lifespan only increases by approximately 0.5 hours.

Increasing WuR range has an ultimately detrimental effect on network lifepan. Longer WuR ranges cause more nodes on average to be awakened per WuS, but also allow for fewer hops to the sink. Conversely, shorter WuR ranges result in more hops to the sink, but fewer nodes awakened at each hop. Fig. 11 depicts the effects of r on network lifespan, with $N = 128$ and $d = 10$ kbps.

The network lifespan is highest at $r = 25$ m. For $\lambda = 12.5$, networks remain alive for approximately 1497.8 hours on average. However, the network lifespan is lowest at $r = 37.5$ m, with networks at the same rate of traffic remaining alive for an average of 1274.28 hours.

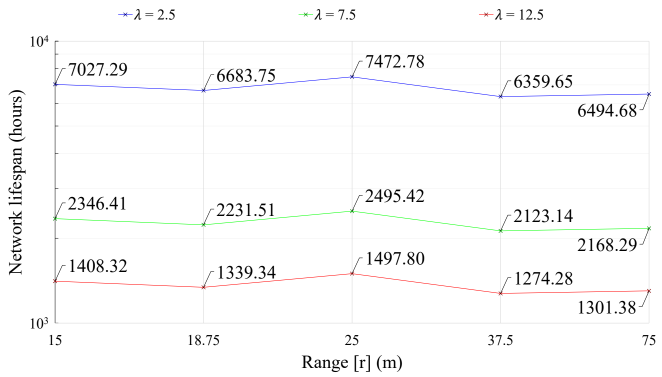

Fig. 11. Range r vs. network lifespan ($N = 128$ and $d = 10$ kbps).

V. RELATED WORKS

WuR technology has been steadily growing in popularity. Various WuR designs have been proposed and studied in detail [3], [26]. New approaches have arisen, and different strategies have been evaluated [2], [29]. These studies have brought to light new challenges and new solutions, including those on the effects of energy harvesting [30], [31] and optimal selection of relay nodes in routes toward the sink [32], [33].

There have been few works on the characteristics of WuRs and their limitations [6]. Various studies have attempted to address these limitations typically focusing on improving particular characteristic of given WuR models, usually accompanied by certain trade-offs. For instance, data rate may be increased at the cost of range or reliability [2]. Effective communication range may be increased at the cost of omnidirectionality [34] or energy efficiency [35]. However, there are also studies that have examined new paradigms in an effort to avoid such trade-offs. New circuit architectures and energy detection techniques have been used to considerably improve bit-rate [36]. Other studies have focused on WuR range [37], [38]. Novel methods, using energy harvesting and antennae diversity, have allowed for substantial improvements in effective communication range [39], [40]. In essence, the past decade has seen a steady trend towards superior WuR characteristic ratios. Yet, so far there have not been any studies into the effects of varied characteristics on network operations and typical network performance as a whole. In our investigation, we consider the effects of varying fundamental characteristics of WuR on key performance metrics. To the best of our knowledge, this is the first time that these effects are considered, which provides useful insights on possible directions for future design of the WuR technology.

VI. CONCLUSIONS

This work has systematically explored the impact of enhanced wake-up radio capabilities on the performance of wireless sensor networks, particularly focusing on energy-aware routing protocols. By extending the communication range and increasing the data transmission rates of WuRs, we demonstrated that significant improvements in network performance metrics such as packet delivery ratio, end-to-end latency, and network lifespan can be achieved, while maintaining the low energy consumption characteristic of WuR-enabled systems. Results show that PDR, latency, energy efficiency, and network lifespan are all significantly improved by increased data rate. Latency also benefits from increased range. However, we observe that PDR benefits from increased range only when data rate is above a threshold, suggesting the need of judicious WuR design trade-offs.

Our study contributes to the ongoing research in WuR technologies by providing a detailed analysis of how specific WuR enhancements can substantially benefit WSN performance. Future research should focus on refining WuR design to optimize these parameters further, potentially integrating adaptive control mechanisms that dynamically adjust range and data rates based on real-time network conditions and requirements. Additionally, exploring the integration of WuRs with emerging Internet of Things (IoT) applications could further delineate the role of WuRs in next-generation networks. In conclusion, the advancements in WuR technology hold promising potential to revolutionize the operational efficiency of WSNs, making them more robust, efficient, and longer-lasting. As WuRs continue to evolve, they are poised to become a cornerstone technology in the deployment of energy efficient WSNs across a multitude of IoT applications.

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