Multi-hop Wake-up Radio Relaying for the Collection Tree Protocol

Abhimanyu Venkatraman Sheshashayee
Institute for the Wireless Internet of Things
Northeastern University
Boston, MA, U.S.A.
abhi@ece.neu.edu

Stefano Basagni
Institute for the Wireless Internet of Things
Northeastern University
Boston, MA, U.S.A.
basagni@ece.neu.edu

***Abstract*—Wake-up radio technology is proving to be an effective strategy for bettering energy efficiency of wireless networks. Nodes can transmit wake-up signals via their wake-up radios (WuRs), thereby preventing the unnecessary power drain of their main radio. In this paper we propose a multi-hop wake-up relay for CTP-WuR, the Collection Tree Protocol modified to work with wake-up radios. We implement and evaluate the performance of our multi-hop relay solution in the GreenCastalia simulator, and we compare its performance to that of baseline CTP-WuR. We also implement and evaluate the protocols on a physical testbed. Our results show the advantage of multi-hop relaying over the baseline implementation with respect to key metrics. Particularly, multi-hop relaying decreases average energy consumption to 78% of the baseline and packet delivery time is reduced to an average of 71% of the baseline.**

***Index Terms*—CTP-WuR, wake-up radio-based networking, multi-hop relaying**

I. INTRODUCTION

Wireless Sensor Networks (WSNs) require the deployment of numerous battery-powered devices that communicate wirelessly. Typically, such setups are beset by short operational lifetimes. This depends on the relatively short life of the batteries powering the network nodes, and on the continuous energy drain due to sensing, nodal processing, and especially to the radio transducers, even when they do not communicate ("idle energy consumption").

Various studies have proposed energy-efficient solutions for all parts of the node architecture and all layers of the networking protocol stack. A recent approach has been the use of *Wake-up Radio* (WuR) technology [1]–[4]. Nodes use an ultra-low-power auxiliary receiver to listen for a wake-up signal. By default, nodes turn off their main radio to enter a 'dormant' state. When a node receives a specific wake-up signal, it switches to an 'active' state, turning on its main radio. When the main radio is no longer in use, the node returns to the dormant state. This approach can significantly reduce the energy consumption of a network, without the penalties of increased latency caused by duty cycling [5]. This has been demonstrated by numerous works [2], [6]–[8].

Most WuR designs are range-based: A WuR broadcast will cause all nodes in range to wake up. However, some designs allow for wake-up signals to carry an address, and have only one or few target nodes become active. Leveraging such designs allow for significantly better energy efficiency [3]. Typically, the main radio has longer range than the WuR [9], [10]. This means that in order to wake up a node that is outside the wake-up radio range, a closer node has to first be awoken. This will require the wake-up signal to be carried over at least one intermediate node, before it can reach it's final destination. Moreover, the intermediate nodes are not awoken; they merely relay the wake-up signal. This is called *wake-up relay* [7]. The benefits of a wake-up relay are obvious: The fewer the nodes that get woken up, the less energy is consumed by the network.

In this paper we propose a multi-hop wake-up relay and demonstrate its benefits to the performance of the Collection Tree Protocol (CTP), a well-known data collection protocol for WSNs [11]. We use the implementation of CTP for WSNs with WuRs presented in [7]. This implementation comes with a single-hop wake-up relay: When a node has a packet to send, it forwards it directly to the parent of its parent, without waking up its parent. This allows nodes that are up to twice the distance of the WuR range from each other to wake each other up. We extend this idea to allow nodes to awaken each other even if they are more than twice the distance of the WuR range apart. Obviously, the wake-up target has to be within the range of the primary radio, or waking it up would be pointless.

The effectiveness of the multi-hop relay is demonstrated by evaluating its performance on a simulator and a testbed. We use the GreenCastalia simulator [12], which is an extension of the Castalia simulator [13]. This is a freely available network simulator that is geared towards wireless sensor networking. Energy consumption, as well as MAC and physical layer aspects of WSNs are realistically modeled within the simulation environment. We use the same simulation scenario as in the CTP-WuR investigation. However, we vary the range of the WuR. We also implement CTP-WuR on a testbed of 11 wireless network motes. The energy consumption and the number of node awakenings are measured. We compare the results of the CTP-WuR implementation from [7] (baseline implementation) with that based on our multi-hop relay mechanism. It is found that the multi-hop relay significantly reduces energy consumption and packet latency. Particularly, multi-hop relaying consumes 78% of the energy consumed by the baseline implementation. We also find that the average packet delivery time is reduced to 71% of that of the baseline.

The remainder of the paper is organized as follows. Section II describes the multi-hop relay mechanism in details. In Section III we elaborate on the architecture of the nodes used in our experiments. Section IV shows the performance evaluation of CTP-WuR with multi-hop relay in comparison with the baseline implementation. The experimental setups (simulations and testbed) are explained, the investigated metrics are defined, and results are shown. In Section V we briefly summarize works related to our research. Finally, Section VI concludes the paper.

II. Multi-hop Relaying for WuR-based Nodes

The setup of the multi-hop relay occurs in 2 phases: *Discovery* and *Exploration*. We first define the relevant notation in Section II-A. We then describe the *Discovery* phase in Section II-B. After that, the *Exploration* phase is described in Section II-C. Finally, we present the operation of CTP-WuR with the multi-hop relay in Section II-D.

A. Notation

Let N be the number of nodes in the network. Each node in the network has a unique "shortened identifier" that can be used in the wake-up signal.[1] Shortened identifiers can be generated via enumeration protocols [14].

Every node v has a list of tuples $L(v) = \{T_1, T_2, \ldots\}$. Each tuple $T_i = \left(R_i, M_i^{Next}, M_i^{Hops}, W_i^{Next}, W_i^{Hops}\right)$, where:

- R is the target node, which the message is meant to ultimately reach. Every $R_i \in L(v)$ is unique.
- M^{Next} is the node that the data packet must be relayed through, via the main radio.
- M^{Hops} is the number of hops that the data packet needs to make to get to the $Target$ node.
- W^{Next} is the node that the wake-up signal must be relayed through, via the WuR.
- W^{Hops} is the number of hops that the wake-up signal needs to make to get to the $Main^{Next}$ node.

However, initially, $L(v) = (v, v, 0, v, 0)$.

B. Discovery

Upon startup, each node waits for a short while, to ensure that all of the other nodes in the network have started. Following this, the discovery phase begins with every node broadcasting its shortened ID, both via the main radio and the WuR. When a node u receives a broadcast data packet from node v, it creates a new tuple $T = (v, v, 1, null, null)$. However, if u receives a broadcast wake-up packet from v, it creates the tuple $T = (v, null, null, v, 1)$. If u has received both a broadcast data packet and a broadcast wake-up packet from v, then it merges the two corresponding tuples into $T = (v, v, 1, v, 1)$. After another short waiting period, the nodes move onto the next phase.

C. Exploration

The exploration phase begins with each node v sending a unicast message via the main radio to every M^{Next} or W^{Next} address in $L(v)$. This message contains all of the tuples in $L(v)$. The message also contains a flag that indicates if the unicast address was in M^{Next} or W^{Next}. When a node u receives a unicast message from v, the following actions are taken for each tuple $T_i \in L(v)$:

1) If $L(u)$ does not contain some T_j such that $R_i = R_j$, then a new tuple $T_k = (R_i, null, null, null, null)$ is created and added to $L(u)$.
    a) If the flag indicates that the unicast address was in M^{Next}, then M_k^{Next} is set to v, and M_k^{Hops} is set to $M_i^{Hops} + 1$.
    b) If the flag indicates that the unicast address was in W^{Next}, then W_k^{Next} is set to v, and W_k^{Hops} is set to $W_i^{Hops} + 1$.
2) If $L(u)$ contains some T_j such that $R_i = R_j$ and $R_i \neq u$, then T_i and T_j are compared.
    a) If the flag indicates that the unicast address was in M^{Next}:
        i) If $M_i^{Hops} + 1 > M_j^{Hops}$, then u unicasts T_j back to v.
        ii) If $M_i^{Hops} + 1 = M_j^{Hops}$, then no action is taken.
        iii) If $M_i^{Hops} + 1 < M_j^{Hops}$, then M_j^{Hops} is set to $M_i^{Hops} + 1$ and M_j^{Next} is set to v.
    b) If the flag indicates that the unicast address was in W^{Next}:
        i) If $W_i^{Hops} + 1 > W_j^{Hops}$, then u unicasts T_j back to v.
        ii) If $W_i^{Hops} + 1 = W_j^{Hops}$, then no action is taken.
        iii) If $W_i^{Hops} + 1 < W_j^{Hops}$, then W_j^{Hops} is set to $W_i^{Hops} + 1$ and W_j^{Next} is set to v.

Finally, for each node v the exploration phase terminates if either:

- A timeout is exceeded, or
- $|L(v)| = N$.[2]

D. CTP-WuR

If the exploration phase was not successfully completed (that is, if the timeout was exceeded before $|L(v)| = N$), then the network will have to repeat the discovery and exploration phases. However, if the exploration phase completes successfully, CTP can begin. The minimum-cost tree is built separately from the relay tuples. Nodes switch to their dormant state after a period of no communication.

---

[1] A "shortened identifier" is a unique sequence of bit identifying the node in the network. It is "shortened" in the precise sense that it is shorter than the 48-bit MAC address of the node wireless interface.

[2] For convenience, we suppose that every node in the network knows the size of the network, as would be the case after the execution of an enumeration protocol [15].

In order for a node v to awaken its parent, it broadcasts two wake-up signals.[3] The first signal contains the address W_i^{Next} where R_i is the target parent. The second signal contains R_i itself. When a node u initially receives a wake-up signal, it assumes that the signal is the first of two. If the the address contained in the first signal is not the same as the address of u, then the node ignores the second signal. If the address contained in the second signal is not the same as the address of u, then the node broadcasts its own pair of signals. However, if the address is the same, the node wakes up. Upon waking up, u broadcasts that it is active via its main radio, which alerts v that it is ready to communicate. Data is forwarded, and the nodes return to their dormant state. In the event that v is not notified that it's parent has become active, v re-broadcasts its wake-up message after a timeout period.

III. NODE CHARACTERISTICS AND SETTINGS

A. Wake-up Receiver

The architecture of the wake-up receiver is illustrated in Fig. 1. This receiver uses On-Off Keying (OOK) modulation, which is one of the more basic forms of amplitude-shift keying modulation. Digital data is represented by a carrier wave, namely, the absence or presence of the same.

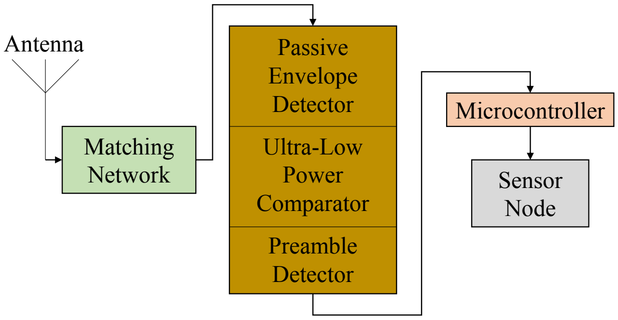

Fig. 1. Architecture of the wake-up receiver.

When a signal is received by the antenna, power is transferred into the circuit via the *matching network*. This module uses an LC filter, designed based on the transmission frequency. Information such as the wake-up sequence can be recovered from the RF signal emitted by the matching network.

Next, the *passive envelope detector* filters out the phase/frequency content of the modulated waveform. Only the amplitude is detected, which is consistent with the use of OOK modulation. This module consists of a single-stage half-wave rectifier with series diodes. Specifically, Avago Technologies' HSMS-285C diodes. These diodes are optimized for frequencies under 1GHz and for incoming power levels that are under -20dBm.

After the signal rectification by the envelope detector, an *ultra-low power comparator* reconstructs the bits of the received wake-up sequence. An adaptive threshold mechanism maintains the V^- pin of the comparator at half of the input signal level, so as to reduce the static power consumption by the circuit. Since the threshold is generated based on the energy coming from the antenna, the use of a voltage divider can be avoided. As the comparator is the only active component of the design, its choice influences both the power consumption and overall sensitivity of the WuR. Generally, comparators with a lower voltage offset can sense smaller signals. However, this would result in greater consumption of current.

Finally, the *preamble detector* is used to prevent interference and unwanted awakenings, which can be caused by noise or other communications. Thus, a preamble is added at the beginning of each wake-up sequence. This preamble is an OOK modulated signal. It represents a specific sequence of bits that is sent at a specific bit rate f_p. The preamble detector discards any OOK modulated signals that are sent at a data rate below f_p. This is done by the RC section, which behaves like a low-pass filter. When a preamble is received, and that preamble is greater than or equal to the f_p bit rate, then the preamble detector generates a wake-up interrupt. This interrupt is sent to a microcontroller that reads the data and performs address matching. If a valid address is received, then the node proceeds to awaken. Further details can be found in [2], [16]

B. Nodes

Our experiments concerns networks of *MagoNode++* motes. The MagoNode++ is a low-power wireless mote featuring an integrated transceiver that uses an IEEE 802.15.4 compliant 2.4GHz radio module [17]. It has an on-board microcontroller featuring a 8-bit, 16MHz CPU, 256KB of ROM, and 32KB of RAM. CSMA is used at the MAC layer of the MagoNode++. The channel data rate is 250Kbps per second. The transmission power is -3dBm.

The wake-up radio is modeled based on the specifications of the previously described wake-up radio receiver prototype that we also used in the testbed [2]. The design consumes very little power (under 1.3μW) while maintaining high sensitivity (up to -55dBm). Here we used the prototype optimized to work in the 433MHz band [18]. Wake-up sequences are sent using the low-power CC1101 transceiver from Texas Instruments [19]. These transceivers are sub-1GHz and support OOK modulation. Each sequence is 1B long, and is transmitted at 1Kbps.The power consumption of the receiver is 1.071μW. The wake-up transmitter and receiver each uses a separate antenna with a 50Ω impedance and gain, which depends on the frequency. This impedance matching was designed to maximize power transfer between the antenna and the rest of the circuit. Magno et al. details the calibration of the matching network [16]. This model also considers the power consumption of the integrated ultra-low power microcontroller used to perform wake-up addressing. The idle and active states consume 0.036μW and 54μW respectively.

---

[3] Each wake-up sequence is 8 bits long, and our network sizes typically have over 32 nodes, which means that multiple addresses cannot fit into the same wake-up sequence [16].

IV. PERFORMANCE EVALUATION

The performance of the multi-hop relay version of CTP-WuR is evaluated simulating networks with varied WuR ranges. We also run the protocol on a testbed of wireless motes with wake-up radios set up indoors in the Northeastern University main campus. We start by defining the metrics investigated in both simulation-based experiments and on the testbed (Section IV-A). After that, Section IV-B shows the results of the simulation-based experiments. Finally, Section IV-C shows the results of the physical testbed-based evaluation.

A. Performance Metrics

1) *Number of awakenings*. This is the number of nodes in the network that were moved from a dormant state to an active state due to the receipt of a wake-up sequence.
2) *Total energy consumption of the network*. This is the sum of the amounts of energy consumed by each node during the execution of the protocol. The bytes of each broadcast packet, the MAC layer overhead, and the overhead from the physical layer are all included in determining the energy needed for transmission and reception. The energy consumed is the product of the average power needed for transmission and reception, the number of bytes transmitted, and the time it takes to transmit or receive those bytes.
3) *Packet delivery percentage*. This is the percentage of data packets that were successfully delivered from source to sink.
4) *End-to-end latency*. This is the average time needed to successfully deliver a packet from source to sink.

B. Simulation-based Comparative Performance Evaluation

The simulation experiments are conducted in GreenCastalia [12]. We consider a network with 64 nodes that are spread across an area that is 227m × 56m. The nodes are deployed in a grid, with an offset of 10% from the corresponding grid point. A packet is generated on average every 60s, following a Poisson distribution. Once a packet is generated, it is assigned to a node (its source) chosen randomly and uniformly among all nodes but the sink. Packet size is set to 70B. We compare the performance of CTP-WuR with and without ("CTP-WuR baseline") the proposed multi-hop relay mechanism. The range of the WuR is varied in $\{15, 25, \ldots, 75\}$m. The range of the main radio is 70m.

The experiments are repeated 400 times, with each instance being 3600s of simulated time. The results are averaged over all of the repetitions. This allows us to obtain 95% statistical confidence with 5% precision. Results are as follows.

Number of awakenings. Fig. 2 presents the number of nodes awakened during the execution of the protocols.

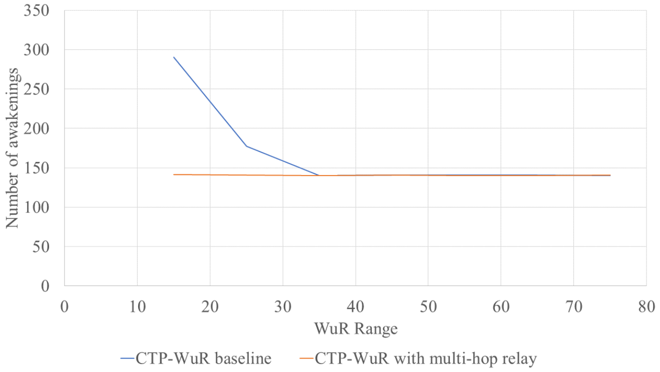

Fig. 2. Number of awakenings.

At shorter WuR ranges, there are significantly more awakenings for the baseline than for the multi-hop version of CTP-WuR. This is because, in the case of the baseline, more nodes need to be awakened due to the limited relay distance. Whereas in the case of the multi-hop relay, there is no limit to the relay distance, so the throttling factor is the main radio range. The awakenings for both the baseline and the multi-hop converge at 35m. At greater WuR ranges, the number of awakenings remain similar.

Energy consumption. Fig. 3 presents the energy consumption of both versions of CTP-WuR. In general, the energy consumption decreases as the WuR range increases. The baseline implementation always sees significantly higher energy consumption for most WuR ranges. At 15m WuR range, the multi-hop relay consumes 46% of the energy consumed by the baseline. On the average, the multi-hop relay consumes 78% of the energy consumed by the baseline. As expected, the energy consumption of the two approaches becomes similar when the wake-up range equates the range of the main radio. When the WuR is guaranteed to communicate with the target node in 1 hop, the multi-hop relay is no longer beneficial. For the baseline, the energy consumed decreases strictly monotonically with increasing WuR range. For the multi-hop relay, the decrease in energy consumption is not strictly monotonic. Between WuR ranges of 25m and 65m the energy consumed varies negligibly. The reason for this is that most of the energy consumption is due to node awakenings. At lower WuR ranges, the energy consumed by the baseline is considerably greater than the energy consumed by the multi-hop relay, reflecting the greater number of nodes awakened. The remainder of the energy consumption is due to the WuR relay. As the

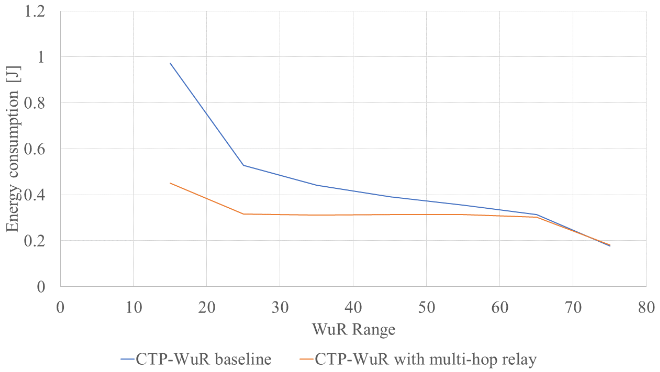

Fig. 3. Total energy consumption of the network.

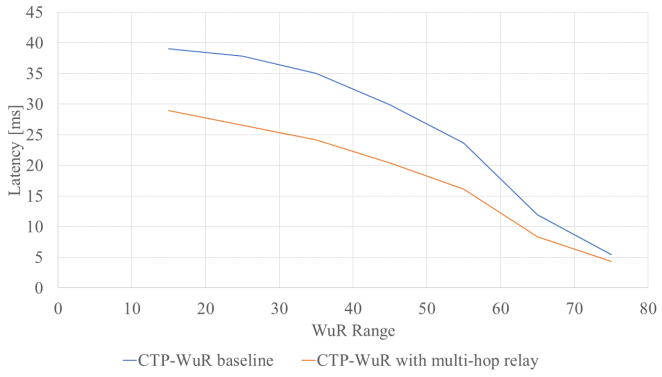

Fig. 4. Latency.

WuR range increases, fewer nodes are needed to relay wake-up sequences, resulting in lower energy consumption. Since the number of awakenings for the multi-hop relay remains consistent regardless of WuR range, the energy consumption mainly reflects the number of wake-up sequences sent.

Packet delivery percentage. Packet delivery occurs over 99% of the time. (As the results is excellent for both protocols, we did not plot the corresponding curves.) The goodness of the results for both protocols mainly depends on the fact that being the traffic fairly low, interference among data packets is also low.

Latency. Fig. 4 presents the average end-to-end latency of packets moving across the network. As the range of the WuR increases, the latency decreases. This is expected as with greater WuR ranges packets move closer to the sinks. At a wake-up range of 45m, latency values are between 20ms and 30ms. On the average, the multi-hop relay delivers packets in 71% of the time taken by the baseline.

C. Testbed-based Evaluation

CTP-WuR and the proposed multi-hop wake-up relay are also evaluated on a physical testbed of 11 MagoNode++ [17]. The testbed is deployed at Northeastern University's Boston campus, on level 4 of Snell Library. Fig. 5 depicts the topology of the network according to the wake-up radio range of 15m. This setting is consistent with results from ranging experiments with our prototype of the WuR [18]. The sink is indicated by a pentagon.

As in the simulation-based evaluation, packets of size 70B are generated on average every 60s. Each instance of CTP-WuR is run for 600s, with 10 repetitions.

The results of the experiments on the physical testbed are listed in Table I. We observe that CTP-WuR with multi-hop relaying achieves approximately the same number of node awakenings as the baseline. This is mainly due to the small network size. The maximum number of hops to the sink is 2, which is fulfilled by both the baseline implementation and multi-hop relay. The energy consumption reflects this, with the multi-hop relay consuming 96% of the energy consumed by the baseline implementation.

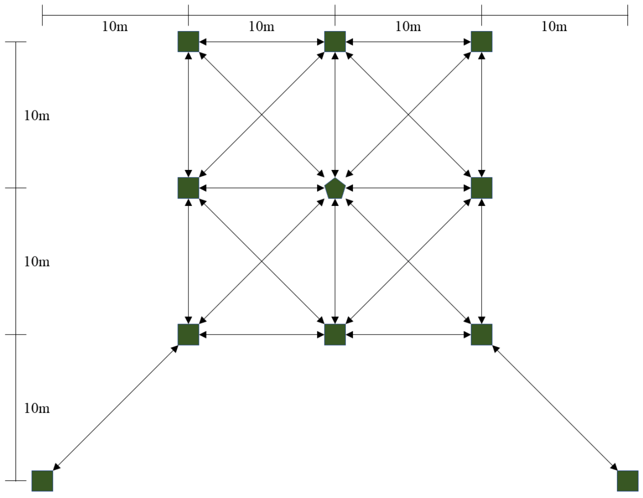

Fig. 5. Testbed topology.

TABLE I
PERFORMANCE RESULTS FOR THE PHYSICAL TESTBED.

	CTP-WuR baseline	*CTP-WuR with multi-hop relay*
Number of awakenings	10.99	10.96
Total energy consumed [J]	0.067471919	0.05444021
Packet delivery percentage	100%	100%
Latency [ms]	5.143331226	3.500051163

To ascertain the accuracy of our simulation results, the physical testbed is replicated in the simulator. The topology and all of the parameters are the same as in the physical testbed (Fig. 5). We run 1000 repetitions of either protocol, for a duration of 600s each. The results of the experiments on the simulated testbed are listed in Table II. By comparing the results of Table I and of Table II we observe that the results from the physical testbed and the simulated testbed topology are in agreement. This validates the results of our simulation-based investigation.

TABLE II
PERFORMANCE RESULTS FOR THE SIMULATED TESTBED TOPOLOGY.

	CTP-WuR baseline	*CTP-WuR with multi-hop relay*
Number of awakenings	10.9164	10.9547
Total energy consumed [J]	0.067955574	0.054485279
Packet delivery percentage	99.99%	99.99%
Latency [ms]	5.142826905	3.515960787

V. RELATED WORKS

WuR technology has steadily been growing more popular for over a decade [9] [20]. Numerous aspects of WuR design space have been examined, and beneficial avenues of research have been identified [1]. Several new methods and technologies have appeared over the last few years [3] [5]. Studies have had diverse approaches to the adaptation and implementation of WuR technology [10] [2]. Some investigations examine energy harvesting techniques in relation to WuRs [21]. Other investigations have focused on augmenting existing protocols [7] [22] [6].

Relaying concepts have shown particular potential. Zhang et al. [23] describe a multi-hop routing protocol with a WuR-based relay. The routing table is built on the basis of the WuR "overhearing." Another study by Djidi et al. [24] proposes an adaptive MAC protocol that leverages relaying by WuRs. The proposed solution is implemented and its performance is evaluated. Micro-benchmarks indicate a $+70\%$ gain in lifetime with 2 relays.

VI. CONCLUSIONS

This paper proposes a multi-hop wake-up relaying mechanism implemented for the WuR-based Collection Tree Protocol. Relaying allows nodes to awaken parents that are separated by more than double the WuR range. The performance of the relay is evaluated via GreenCastalia-based simulations. Both the baseline protocol CTP-WuR and the multi-hop relay version are run on wireless networks whose nodes have varying WuR ranges. Our results show that multi-hop relaying significantly improves energy efficiency. Subsequently, both protocols are implemented on a testbed and evaluated. Then, the testbed is recreated in the simulator and evaluated. The physical testbed and simulated testbed are compared, and their results are found to be similar, thereby validating our simulation results.

REFERENCES

[1] R. Piyare, A. L. Murphy, C. Kiraly, P. Tosato, and D. Brunelli, "Ultra low power wake-up radios: A hardware and networking survey," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 4, pp. 2117–2157, Fourthquarter 2017.

[2] D. Spenza, M. Magno, S. Basagni, L. Benini, M. Paoli, and C. Petrioli, "Beyond duty cycling: Wake-up radio with selective awakenings for long-lived wireless sensing systems," in *Proceedings of IEEE Infocom 2015*, Hong Kong, China, 26–30 April 2015, pp. 522–530.

[3] C. Petrioli, D. Spenza, P. Tommasino, and A. Trifiletti, "A novel wake-up receiver with addressing capability for wireless sensor nodes," in *Proceedings of IEEE DCOSS 2014*, Marina Del Rey, CA, USA, 26–28 May 2014, pp. 18–25.

[4] J. Oller, I. Demirkol, J. Casademont, J. Paradells, G. U. Gamm, and L. Reindl, "Performance evaluation and comparative analysis of subcarrier modulation wake-up radio systems for energy-efficient wireless sensor networks," *Sensors*, vol. 14, no. 1, pp. 22–51, 2013.

[5] S. Basagni, F. Ceccarelli, F. Gattuso, and C. Petrioli, "Demo abstract: Abating LPL-induced latency with wake-up radio technology," in *Proceedings of ACM IoT DI 2017*, Pittsburg, PA, USA, 18–21 April 2017, pp. 1–2.

[8] T. Kumberg, M. Schink, L. Reindl, and C. Schindelhauer, "T-ROME: A simple and energy efficient tree routing protocol for low-power wake-up receivers," *Ad Hoc Networks*, February 2017.

[6] S. Basagni, V. Di Valerio, G. Koutsandria, C. Petrioli, and D. Spenza, "WHARP: A wake-up radio and harvesting-based forwarding strategy for green wireless networks," in *Proceedings of IEEE MASS 2017*, Orlando, FL, USA, 24–27 October 2017, pp. 257–265.

[7] S. Basagni, C. Petrioli, and D. Spenza, "CTP-WUR: The collection tree protocol in wake-up radio WSNs for critical applications," in *Proceedings of IEEE ICNC 2016*, Kauai, HI, USA, 15–18 February 2016, pp. 1–6.

[9] L. Chen, S. Cool, H. Ba, W. Heinzelman, I. Demirkol, U. Muncuk, K. R. Chowdhury, and S. Basagni, "Range extension of passive wake-up radio systems through energy harvesting," in *Proceedings of IEEE ICC 2013, Ad Hoc and Sensor Networking Symposium*, Budapest, Hungary, 9–13 June 2013, pp. 142–147, best Paper Award.

[10] L. Chen, J. Warner, P. L. Yung, D. Zhou, W. Heinzelman, I. Demirkol, U. Muncuk, K. R. Chowdhury, and S. Basagni, "Reach^2-mote: A range extending passive wake-up wireless sensor node," *ACM Transactions on Sensor Networks*, vol. 11, no. 4, pp. 64:1–64:33, December 2015.

[11] O. Gnawali, R. Fonseca, K. Jamieson, M. Kazandjieva, D. Moss, and P. Levis, "Ctp: An efficient, robust, and reliable collection tree protocol for wireless sensor networks," *ACM Transactions on Senor Networks*, vol. 10, no. 1, pp. 16:1–16:49, December 2013.

[12] D. Benedetti, C. Petrioli, and D. Spenza, "GreenCastalia: An energy-harvesting-enabled framework for the Castalia simulator," in *Proceedings of ACM ENSSys 2013*, Rome, Italy, 11–14 November 2013.

[13] A. Boulis, "Castalia: Revealing pitfalls in designing distributed algorithms in WSN," in *Proceedings of ACM SenSys 2007*, Sydney, Australia, 6–9 November 2007, pp. 407–408.

[14] A. V. Sheshashayee and S. Basagni, "Wienum: Node enumeration in wireless networks," in *Proceedings of MILCOM 2015*, Tampa, FL, USA, 26–28 October 2015, pp. 1027–1032.

[15] J. Evers, D. Kiss, W. Kowalczyk, T. Navilarekallu, M. Renger, L. Sella, V. Timperio, A. Viorel, S. van Wijk, and A.-J. Yzelman, "Node counting in wireless ad-hoc networks," *Proceedings of ESGI 79*, 24–28 January 2011.

[16] M. Magno and L. Benini, "An ultra low power high sensitivity wake-up radio receiver with addressing capability," in *Proceedings of GROWN Workshop*, October 2014, pp. 92–99.

[17] M. Paoli, D. Spenza, C. Petrioli, M. Magno, and L. Benini, "MagoNode++: A wake-up radio-enabled wireless sensor mote for energy-neutral applications," in *Proceedings of ACM/IEEE IPSN 2016*, 11–14 April 2016, pp. 1–2.

[18] S. Basagni, F. Ceccarelli, C. Petrioli, N. Raman, and A. V. Sheshashayee, "Wake-up radio ranges: A performance study," in *Proceedings of IEEE WCNC 2019*, Marrakech, Morocco, 15–19 April 2019.

[19] T. Instruments, "CC1101 datasheet," rev. SWRS061I, 2013.

[20] S. Basagni, G. Koutsandria, and C. Petrioli, "A comparative performance evaluation of wake-up radio-based data forwarding for green wireless networks," in *Proceedings of IEEE ICCCN 2018*, Hangzhou, China, 30 July–2 August 2018, pp. 1–9.

[21] K. Kaushik, D. Mishra, S. De, J.-B. Seo, S. Jana, K. R. Chowdhury, S. Basagni, and W. Heinzelman, "RF energy harvester-based wake-up radio for WSNs," in *Proceedings of IEEE Sensors 2015*, Busan, South Korea, 1–4 November 2015, pp. 1–4.

[22] S. Basagni, V. Di Valerio, G. Koutsandria, and C. Petrioli, "Wake-up radio-enabled routing for green wireless sensor networks," in *Proceedings of IEEE VTC 2017 Fall*, Toronto, Ontario, Canada, 24–27 September 2017, pp. 1–6.

[23] Y. Zhang and G. Dolmans, "Wake-up radio assisted energy-aware multi-hop relaying for low power communications," in *Proceedings of IEEE WCNC 2012*, Paris, France, 1–4 April 2012, pp. 2498–2503.

[24] N. E. H. Djidi, A. Courtay, M. Gautier, and O. Berder, "Adaptive relaying for wireless sensor networks leveraging wake-up receiver," in *Proceedings of IEEE ICECS 2018*, Bordeaux, France, 9–12 December 2018, pp. 797–800.