Multihop Networking for Intermittent Devices

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ABSTRACT

Energy harvesting (EH) devices without batteries can enable the Internet of Things (IoT) to reach new and challenging scenarios. Multihop routing is needed to extend the range but, when low EH causes intermittency, it has been overlooked and is not possible with existing protocols. Also, whilst wake-up receivers (WuRxs) have been used to enable star networks, the cost of another EH node sending wake-ups, required for multihop communication, has not been considered. This paper adapts the opportunistic RPL (ORPL) protocol to make possible multihop routing between intermittently-powered devices. Furthermore, the benefit of using WuRx to enable networks is measured, considering different sensitivity devices and associated range. Comparing ORPL to RPL, we show that opportunistic routing enables multihop communication where RPL cannot. If WuRx are used for routing towards a central hub, the more sensitive WuRx perform better, but routing cross-network benefits from lower sensitivity, lower power WuRx.

CCS CONCEPTS

• **Networks** → **Cross-layer protocols**; **Network simulations**; • **Computer systems organization** → **Sensor networks**.

KEYWORDS

Batteryless sensors, Wake-up Receiver, Intermittently-powered

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1 INTRODUCTION

The rise in interest in Internet of Things (IoT) devices and pervasive sensing requires solutions that are low maintenance and that operate for a long time [20]. This motivates research to improve the energy supply with energy harvesting (EH), maximize computation with more efficient microprocessors and also novel operation in response to varying EH, which causes intermittency [17]. Irrespective of application, the devices must wirelessly exchange measurements, local information, sensing demands and operational information. Whilst a majority of data is routed to a data collection hub, routing must also be possible between devices in the network.

To operate intermittently, recent work using EH has used intermittent computing (IC) to perform computation across power cycles, but these devices often operate alone [17]. This is because of the relatively large power consumption required for communication. Of the few that have considered communication [3, 20, 22], they mainly consider using sensitive listening base stations using technologies like LoRa or harnessing radio frequency (RF) EH from base stations transmitting at up to 3 W. These still require higher base station energy consumption and cannot communicate out of range of the fully powered base station, limiting it to star networks.

Additionally, whilst scheduled medium access control (MAC) techniques can reduce the listening cost, frequent power losses in intermittent devices means the cost of resynchronizing becomes too high [9]. Instead, wake-up receivers (WuRxs) are a facilitator of unsynchronized communication between EH powered homogeneous devices but with reduced sensitivity, and therefore range. This increases the need for multihop networking, since high power transmissions are unfeasible. In that respect, there is also a previously uninvestigated trade-off between reducing power consumption (and also range) and increasing the number of hops [24].

Multihop networking uses multiple hops through other devices, termed nodes, to reach destinations beyond the initial range. Multihop protocols have been considered for low power devices, for example with duty cycling in opportunistic RPL (ORPL) [5] and load balancing in Econcast [2] to increase the lifetime of a battery based system. However, they rely on large energy buffers to sustain routes and controllable duty cycles, or do not support cross network routing. Instead, multihop networks with only limited EH and storage are desired.

Therefore to advance IoT networks with intermittently-powered nodes and to measure the enabling capability of WuRx for communication at sub-mW levels, this paper makes these contributions:

- Definition of cross layer MAC overhearing interfaces to reduce control messages and development of intermittent ORPL metric, EqDC, to make intermittent multihop networking possible.
- Comparison of intermittent ORPL in intermittently powered scenario, with the Routing Protocol for Low Power and Lossy Networks (RPL) running from mW EH power.
- Evaluation of 4 different sensitivities of WuRxs to enable multihop cross network routing with µW EH levels, where WuRx sensitivity non-trivially affects routing performance.

*E. Longman produced this work with supervision from M. El-Hajjar and G. Merrett. Simulation code and data is available at https://doi.org/10.5258/SOTON/D2405.

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Model Name	Sensitivity (dBm)	Bitrate (kbps)	t_{WU} (ms)	P_{Li} (µW)	P_{Rx} (µW)	Filter Type§
Hambeck1 [6]	-64	200	1	3		D
Hambeck2* [6]	-71	200	5	3		D
Wenzloff1 [18]	-41	n/a	10	0.392		N
Wenzloff2 [14]	-43	12.5	5	0.8544	0.8544	S
Milosio1 [12]	-82	8.1		240		D
Milosiu2 [12]	-82	1		31.3		D
Abe* [1]	-87	50	1	88.4	1576.8	D
Moazzeni* [13]	-75	200	0.9	32.8	45.8	D
Magno1 [10]	-32	8.3		0.48	63	D
Magno2 [10]	-42	8.3		0.81	63	D
Magno3* [10]	-55	8.3		1.77	63	D

Table 1: Models of state of the art WuRx with varying sensitivity, capabilities, and listening power, P_{Li}. Wake-up duration, t_{WU}, and receiving power, P_{Rx}, only applicable to some WuRx. All adjusted for 3 V operation. *indicates WuRx used for results. §Three filter types are None, Static and Dynamic.

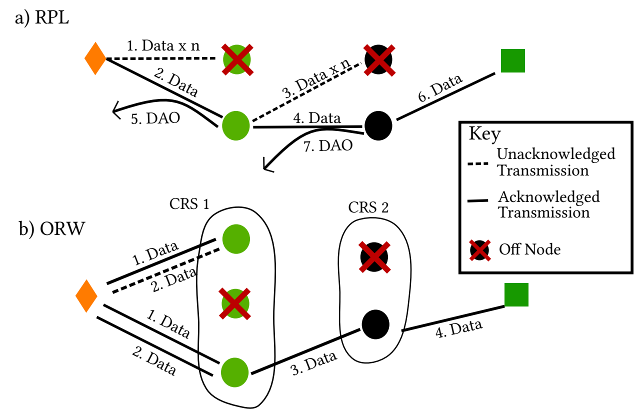

Figure 1: Comparison of (a) multihop intermittent communication with RPL and (b) opportunistic routing for WSN (ORW), routing upwards (left to right) to a hub (green square) from a packet source (orange diamond) via cooperative intermittent nodes (circles). The next hop is intermittent for both hops, only part of the CRS is shown.

2 RELATED WORK

Following the identification of WuRx as candidates for EH communication, a review of the RF wake-up technology is presented. This provides the basis on which the WuRx models are built for the network simulation. Following this, existing multihop routing techniques suitable for constrained devices in IoT networks are discussed, focussing on the problems caused by intermittency.

2.1 RF wake-up and backscatter

RF wake-up uses the intrinsic power transmitted with a wireless communication to reduce the power consumed from the listening node's energy storage. Most simply, a rectifying antenna (rectenna) can be used to generate a voltage signal with received RF power exceeding a certain level, whilst consuming no stored energy. This has been demonstrated to work at a range of 10 m [23] but using a 3 W transmitter. Alternatively, backscatter uses the incoming RF to generate a response in the reflection of the incoming carrier [7]. However, like rectennas, this requires higher power transmissions, so that there is sufficient power in the reflection. In both methods, the combined low data rates and power mean the energy requirements are prohibitive for homogeneous EH nodes [9].

Alternatively, WuRxs have increased sensitivity and decoding capabilities, like a main radio, but consume orders of magnitude less power for listening in the order of µW. This reduces the power requirements of the transmitter within the capability of EH batteryless nodes. Wentzloff [24] gives an extensive overview of integrated CMOS state of the art WuRx.

Whilst rectennas have the smallest consumption, their low sensitivity means that the high power transmissions are required to trigger the energy detection threshold. Alternatively, whilst it is beneficial to increase the sensitivity of receive radios, this generally comes with increased power consumption cost. Earlier analysis of EH nodes including the transmission cost [8] shows potential increased throughput with higher power transmissions and by reducing WuRx sensitivity accordingly.

Additionally, whilst the sensitivity is an important factor, there are others to consider, especially when they would affect a cooperative EH forwarder. The datarate affects the transmitter, which increases the length of transmissions and power consumption proportionally. At the receiver, there is a difference between selective and non-selective WuRx, where energy is saved by reducing false wake-ups and associated energy consumption. Radios from 6 different authors were explored in detail, chosen as the lowest power at a range of sensitivities [24] and shown in Table 1. We consider the radios at the 900 MHz band, chosen for a good balance of propagation characteristics, antenna size and amplifier efficiency.

2.2 Low-power networking

First considering more conventional protocols, Ad hoc on-demand vector routing (AODV), [4] which has been extended with AODVv2 (DYMO) [15] is designed for Mobile Ad Hoc networks. Route requests are broadcast messages that are flooded until a node knowledge of the destination sends a route reply message. However, it expects fairly static end-to-end behavior until a node moves out of range, which is not the case with intermittent nodes. Additionally the process of the route request is likely to exhaust the supplies of the potential forwarding nodes.

Similarly, the BLITZ protocol [21], uses WuRx broadcast and forward setup a one hop data transmission route with higher capability data radios. However, all hops must have enough energy to instantly forward the message and all wake-up energy is wasted if the destination is unavailable.

The Routing Protocol for Low Power and Lossy Networks (RPL) uses a resource light, tree structure with a central node, termed hub. Messages from the outer nodes are routed up to the central node using a rank (hop count) metric, different to a star network because it takes place in multiple hops. When a parent node becomes unavailable or unreachable, RPL switches to a backup parent.

Figure 1(a) shows RPL behavior under intermittent conditions with the wasted transmissions, new parent selection messages and also additional DODAG advertisement objects (DAOs).

On the other hand, opportunistic routing (OR) uses a candidate relay set (CRS), chosen to make progress towards the destination where the next hop is determined at transmissions time. Smart Gossip [16] uses MAC broadcast to forward the messages to several listening devices which then retransmit the message based on a gossip parameter, not resending overheard messages. However, EH nodes may not be able to immediately retransmit and, when sleeping, will not overhear the other retransmissions, causing a broadcast storm.

A close analogue to the unavailablilty of intermittently-powered nodes is the quickly fading channels in wireless mobile environments. For this CL-EE [25] was designed, where an in depth analysis shows how optimal forwarders can be chosen in a OR scheme. This increases control messages and resource requirements, especially when there are multiple destinations, beyond what is reasonable for EH nodes. However it only considers optimizing transmission power and requires accurate node position information.

To meet the reduced resource requirements, ORPL/ORW is a redesign of RPL which uses the Expected Duty Cycles (EDC) metric to dynamically choose the forwarding set [5], instead of a single forwarder, illustrated in Figure 1(b). The single metric keeps resource requirements low, and downward routing only requires lightweight "bloom" tables, not complete hop-by-hop route recording. The variety of available forwarders in the CRS means after two transmissions it has been forwarded to CRS 1. The protocol calculates the maximum value of EDC for any CRS node, like the rank metric in RPL, nodes with a lower EDC value, contend to become the forwarder at the MAC level. Furthermore, by sharing the downward nodes set it allows for full upwards and downwards routing [5], but without the hard single node failure points of RPL.

3 ENABLING MULTIHOP NETWORKING FOR INTERMITTENT SYSTEMS

This paper considers EH networks where communication beyond the range of a single node requires multihop routing. Additionally, since the computing and memory capability of the devices is limited, lightweight methods in these respects are required. In a sensor network the data requirements are typically low, but using the available energy effectively is very important.

The nodes in the network use EH to charge energy storage, and when the EH cannot sustain continuous operation, the nodes operate intermittently. The modelled network assumes that there is a central coordination node, termed a hub, that may have higher EH than the other nodes, but it is not assumed that it will be continuously powered either. The remaining nodes in the network all have the same communication hardware and energy storage.

Routing takes place by forwarding data between cooperative, but intermittently powered nodes, where the position and availability of the nodes determines which nodes takes on the task of forwarding. Messages are forwarded until it reaches its destination or the routing or MAC layer drop it due to too many retries.

In addition, we consider the benefits from µW listening with WuRx, where in a multihop network of homogeneous nodes, the

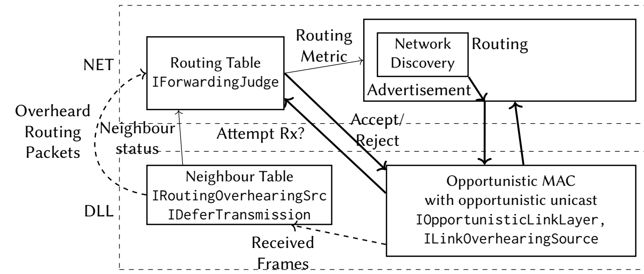

Figure 2: Layers diagram of proposed stack for opportunistic routing (OR), adding overhearing interfaces at MAC and routing layers, and separated neighbor prediction models.

power consumption of wake-up transmission must be considered, and secondly as the sensitivity is decreased it increases the number of hops required to deliver the message, affecting the routing. We compare different WuRx from Table 1 to quantify this effect.

3.1 Proposed cross-layer interfaces

To achieve multihop routing with devices that are intermittent, OR is needed to overcome the variability in individual links between nodes. ORPL overcomes link-variability by using the EDC metric to route upwards towards a central node [5]. The EDC estimates the number of node duty-cycles required to reach the destination based on the probability of reaching the next hop, $p(i \rightarrow j)$, and the EDC value of that node, learned from update control messages.

Reducing the requirement for control messages reduces the energy overhead of the protocol. Since ORPL requires EDC information for data routing, the EDC information does not need explicit sharing. Instead, we introduce cross-layer interfaces to allow the routing protocol to overhear relevant encounters from the MAC layer as exposed by the interface `ILinkOverhearingSource`. The interfaces clearly separate MAC and routing responsibilities but allows the routing layer to overhear messages for creating a preferred forwarder list and calculating the EDC metric.

Additionally, ORPL requires the MAC layer to partake in packet acknowledgement, dependant on the routing table response to the received EDC information. This decision to enter acknowledgement is delegated to the routing layer with the `IForwardingJudge` interface. The MAC interface `IOpportunisticLinkLayer`, compliments this. These interfaces are illustrated in Figure 2 and also enable dynamic wake-ups with WuRx to reduce false wake-ups.

3.2 Intermittent ORPL

The metric calculation for EDC uses the self-reported duty cycle of neighboring nodes of i in the forwarding set, $F(i)$, as in (1)[1], where $p(i \rightarrow j)$ is a product of the duty cycle and link loss probability, and where $\mathrm{EDC}(j)$ is received from node j transmitting its EDC value.

$$\mathrm{EDC}(i) = \frac{1}{\sum_{j \in F(i)} p(i \rightarrow j)} + \frac{\sum_{j \in F(i)} p(i \rightarrow j)\mathrm{EDC}(j)}{\sum_{j \in F(i)} p(i \rightarrow j)} + w. \quad (1)$$

However, this relies on the assumption that nodes can calculate their own duty cycle, which is not possible with intermittently powered nodes. Power outages prevent timers that measure the

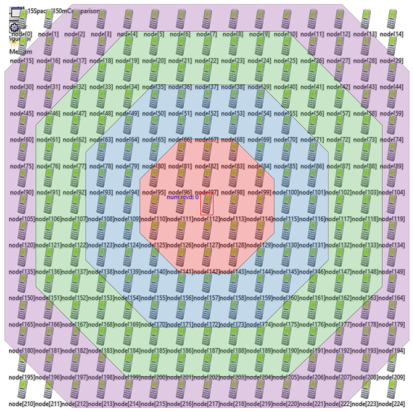

Figure 3: 15x15 grid of energy harvesting nodes with the hub node[112] at the centre. Nodes in the red zone are within 1 hop, blue zone 2 hops, etc.

off-time, which is required for duty cycle reporting. Instead, we use the aforementioned overhearing of messages from the MAC layer to estimate the probability of encountering each neighbor.

The new metric, equivalent duty-cycles (EqDC), uses encounters reported by `ILinkOverhearingSource` to calculate $p(i \rightarrow j)$. Using weightings according to if encounters were expected in (1). If an encounter is received "coincidentally" (like advertisments and messages), then it has a weighting of 2, and the total number of encounters is increased by 1. "Expected" encounters are received when there is an acknowledgement period after transmitting a message. These are weighted according to which contention round the encounter occurs in $\frac{0.8}{2^{round-1}}$. The total number of encounters is only increased by 1 for each transmission, not contention round.

The probability of a neighbour, n, being in range is then calculated from the sum of weighted, w, encounters with n divided by the total number of encounters.

$$p(i \rightarrow j) = \frac{\sum_{enc_j} w}{enc} \tag{2}$$

$$w = \begin{cases} 2, & \text{Coincidental} \\ \frac{0.8}{2^{round-1}}, & \text{Expected} \end{cases} \tag{3}$$

In intermittent ORPL the approximation in (2) is substituted into (1) to make the EqDC metric.

4 SIMULATION SETUP

In order to analyse the performance of opportunistic routing for intermittently powered networks and measure multihop communication with WuRx, we now present our simulation setup. We use OMNeT++, a simulation framework including the INET component library of radio models, energy storage and routing protocols.

The network simulation uses a 15 × 15 grid of intermittently-powered nodes as shown in Figure 3. The nodes are grouped according to the hops required to get to the destination, to measure delivery rate from each group. The same layout is used in all experiments; however in the WuRx comparison, the distance between the nodes is smaller, to reflect the reduced range of the nodes.

4.1 Investigated parameters

Nodes use EH where the EH power is the same for all the nodes within a simulation setup, with the exception of the central node which is permenantly powered. The rate of EH determines the amount of communication possible for the nodes, which is varied to determine the level of EH required to support multihop networking in upwards and downward directions. Additionally, the load interval parameter is set at the application level per node and determines the overall network load. The performance is measured according to the packet delivery rate at the destination node, with separate statistics recording for each source.

4.2 Physical layer modelling

The two slope path loss model is an appropriate fit to sensor networks physical environment [11], where the parameters used in our experiments are a path loss exponent of 2.34 up to 6.2 m and 2.73 for longer distances. This model also includes interference from neighboring nodes blocking complete reception, but not the capture effect or bit error losses at the sensitivity threshold.

All nodes use a data radio model of a CC1120 900 MHz 200 kbps radio from Texas Instruments, which handles medium contention, data and acknowledgement communication. The node power consumption is dominated by the radio which uses a state based power consumption model with listening power consumption of 6 mW and transmitting at +0 dBm consuming 75 mW. The wake-up transmissions are modelled in the WuRx component but could be modelled in the data radio in a high power configuration in real devices.

4.3 Wake-up receiver modelling

The WuRx model considers datarate, transmission consumption, receiver sensitivity, preamble duration, state transmission times and wake-up filtering capability. WuRx are sent wake-up messages, including some OR metric information, from +15 dBm transmissions from the data radio. Four WuRx from Table 1, indicated by *, are demonstrated in this paper, for a wide range of sensitivities from −55 dBm to −87 dBm.

The WuRx MAC layer extends ORPL MAC, determining if a wake-up is appropriate with the `IForwardingJudge` interface.

4.4 Methodology

Each experiment records statistics over 8000 s and several repetitions with randomized initial conditions to provide a confidence level in the results. Only three repetitions are needed for the RPL comparison with intermittent ORPL, where the variation with data radios is small. Five repetitions are used for ORPL experiments where performing more repeats enables sufficiently high confidence in the performance. For three repeats, the uncertainty bands (where shown) represents the maximum and minimum of the measured results. For five repeats, unless otherwise specified, the uncertainty bands represents the 90 % confidence interval for the results collected. Each parameter combination is run independently and the results are compared accordingly.

ORPL has been implemented from scratch in OMNeT++ 6 to allow for adaption for an EH intermittent system. The RPL implementation from Shudrenko [19] runs in OMNeT++ 5.6 with minor modifications to maintain routing tables on shutdown.

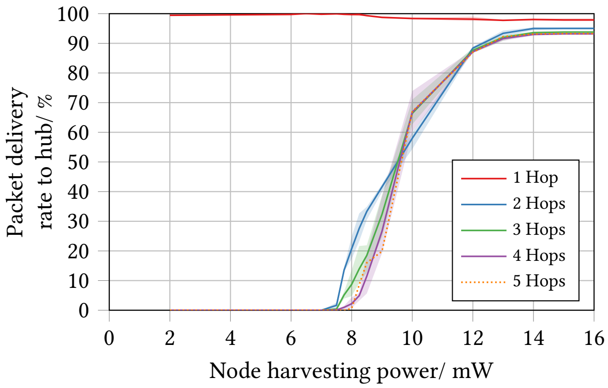

Figure 4: Packet delivery rate to the central node of a 15x15 grid of RPL nodes grouped by approximate hops required. The coloured bands show the range in the results from 3 repetitions, the uncertainty is high for 5 hops due to the small set size and is not shown.

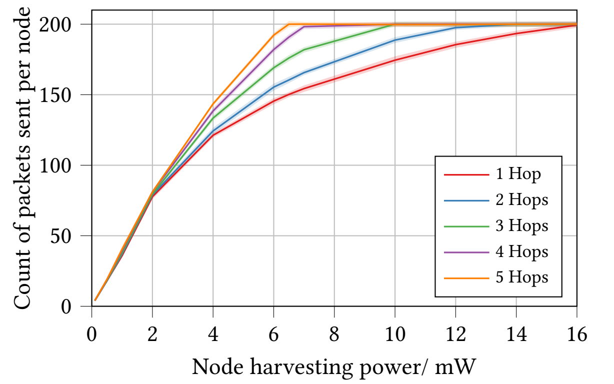

Figure 5: Total number of packets sent by nodes running intermittent ORPL to route data at fixed intervals to the hub. Packets sent affected by limited node harvesting power. Grouped by estimated number of hops to hub.

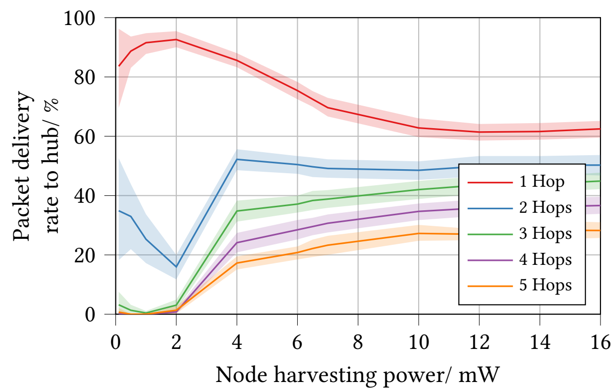

Figure 6: Packet delivery rate calculated per sender at the hub. The nodes have a CC1120 radio and use intermittent ORPL, packet delivery rate max and min shown by shading.

5 RESULTS

In this section we describe the distinctive elements of each experiment. Firstly the RPL protocol is compared to ORPL without WuRx and with EH power in the mW range. The delivery rate across multiple hops is compared across progressively decreasing EH to demonstrate how intermittent ORPL performs. Given the improved performance with OR, WuRx enabled nodes using the ORPL protocol are tested to further reduce power consumption. First upwards only routing is tested before comparing cross network node to node communication with an intermittently powered root node.

5.1 RPL comparison with intermittent ORPL

To test how RPL behaves under intermittency we setup a data collection scenario as in Figure 3, with a node spacing of 150 m. The CC1120 radio, which has a range of 375 m, results in the shown shaded hop groups. The same data radio and grid layout was also tested with intermittent ORPL.

The load interval of 40 s is used and the load is maintained even at low EH power. The packet delivery rate in Figure 4 shows that nodes in immediate range of the hub are not impacted at all, because the hub is permanently powered. For other hops, when not intermittent at EH above 12 mW, the delivery rate is over 95 %, where a small number are lost due to collisions.

However nodes 2 or more hops away show a collapse in delivery rate when intermittency occurs. When the experiments were conducted with a load interval of 70 s (not shown here) the results were the same, but the collapse happens 2 mW lower. Even though the listening power consumption is 6 mW the intermittency occurs at a higher EH power due to the power consumed for transmitting.

The sudden collapse in delivery rate is caused by a storm of tree update control messages. An unavailable next hop will not only cause retransmission, but also a DAO which will propagate down the tree. These subsequent extra transmissions further exhaust already depleted nodes so they cannot listen or forward data. The 2 hop nodes shows a drop at a higher level because they consume energy to forward on behalf of other hops.

Taking the same node configuration in Figure 3, the routing can instead be done opportunistically, using intermittent ORPL. The measured actual load sent over 8000 s is shown in Figure 5 . The per node delivery rate is averaged across the nodes in each hop group and is shown in Figure 6.

At higher EH rates the high node availability leads to long forwarding contention and acknowledgement periods, therefore leading to worse performance in intermittent ORPL than RPL. Whereas, at lower EH power below 10 mW, with a reduced node availability, the delivery ratio is maintained due to multiple candidate forwarders providing redundancy. As the power is reduced, the number of packets sent reduces, shown in Figure 5, which improves the performance of 1 and 2 hop routing at a very low EH power because they are using less energy for cooperative forwarding.

The distance to the hub (in hops) also affects the performance. Within 1 hop the packet delivery rate is highest but, unsurprisingly,

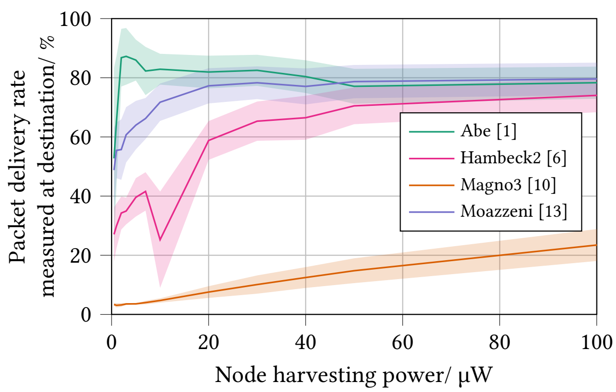

Figure 7: Packet delivery rate for WuRx, sending packets upwards to always-on hub at an interval of 200 s, with all requiring multiple hops (except the Abe WuRx).

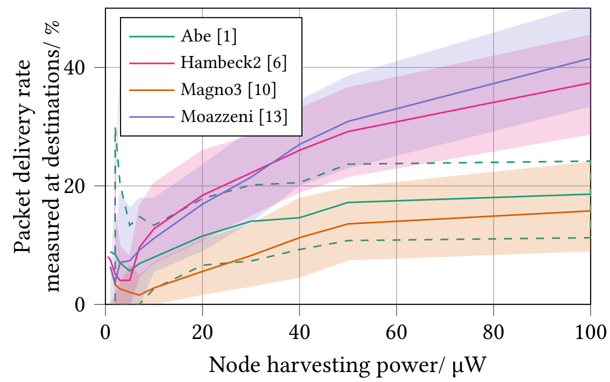

Figure 8: Packet delivery rate in a downward routing scenario for different WuRx, for a transmitting node load interval of 120 s and an intermittent hub. Shading showing greater spread of results with Abe shown with dotted lines for clarity.

there is a reduction in delivery rate over more hops. However, the reduction is not compounded, i.e. 60 % of 60 % for two hops, since there is greater routing diversity further from the hub.

Intermittent ORPL continues to be able to deliver 50 % of packets from 2 hops and 45 % of packets from 3 hops at a EH power 1/4 of the RPL collapse point. For multihop delivery, RPL cannot provide routing but ORPL demonstrates the resilience to intermittency.

5.2 Wake-up Radio Comparison

The investigation of WuRx sensitivity with multihop routing uses 15 dBm transmissions to improve the transmitter efficiency and achieve sufficient range with reduced sensitivity. The models chosen from Table 1 are Magno3, Hambeck2, Moazzeni and Abe with approximate ideal range of 40 m, 100 m, 200 m and 300 m respectively. The EH rate is 100× smaller than the previous scenario ranging up to 100 µW and the node spacing is reduced to 20 m, but due to the use of WuRxs, it is still able to maintain a load interval of 200 s down to 10 µW before the transmission rate drops off.

First, looking at the upwards (to the hub) routing, each received packet is counted at the routing hub, and recorded per source node. Thus, the average delivery rate is calculated and compared across each WuRx model as shown in Figure 7. The Abe configuration is effectively acting as a star network since the range covers the entire network, and it therefore has a consistent delivery rate across the full range of harvesting power. The Moazzeni radio requires two hops in about half of cases, but achieves similar packet delivery rate even at low EH power. Since there is a chance of loss at each hop the increased hops required with the Hambeck2 and Magno3 configurations, their performance is worse. Even though the Abe and Moazzeni duty cycle is small, because the hub is powered, and there are few hops the upwards performance is good.

Secondly, to determine if the best radio for upwards routing negatively impacts the downwards (away from the hub) routing, we now test transmitting cross-network traffic. In this configuration only 45 nodes are transmitting the load, with 22 transmitting to the hub (node 112) and 23 transmitting to 12 receiving nodes 21, 31, 41, 51, 111, 131, 141, 151, 161, 181, 191 and 201, chosen to provide a spread of positions near and far from the hub. The load interval is set at 120 s and the hub is intermittently powered.

This scenario, shown in Figure 8 highlights the advantages of the lower power WuRx, where the higher sensitivity Abe WuRx does not perform so well. Due to the higher power consumption with the Abe radio, end nodes have a short duty cycle so the downwards routing success is significantly lower than both the Hambeck and the Moazzeni devices. The duty cycle of end nodes is reduced by the radio listening consumption, resulting in dropped transmissions at the final hop. For the Abe radio this is particularly apparent, where a harvesting rate of 40 µW would limit the duty cycle to less than 50 %, before accounting for the transmission cost. Even though the Hambeck2 WuRx requires twice the number of hops as Moazzeni, the improvement in duty cycle counteracts this resulting in the same performance for both.

In both upwards and downwards scenarios the Magno3 device has performed badly as the range leaves insufficient candidate relays, with 8 neighbors allowing only 3 or 4 in each direction.

6 CONCLUSIONS

To address the need for multihop communication this paper presented intermittent ORPL. The OR provides redundancy as nodes become intermittent and the cross-layer overhearing reduces the need for control messages. Consequently, simulation results show ORPL outperforms RPL when EH causes intermittency.

Whilst the delivery ratio using ORPL shows a lower maximum success than RPL when fully powered, the implementation has demonstrated its suitability for intermittently-powered networks. Furthermore, WuRx further reduces the power consumption and shows consistent performance across multiple hops, but simulations show that increasing power consumption to increase sensitivity must especially consider downwards routing performance.

Future work should investigate other network densities, improve downwards multihop communication, and consider receiver initiated last hop communication.

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